Renewable and Sustainable Energy Reviews 41 (2015) 1128–1166

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

Biomass cookstoves: A review of technical aspects

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A R T I C L E I N F O

Article history:
Received 24 July 2013
Received in revised form
3 September 2014
Accepted 3 September 2014

Keywords:
Cookstoves
Biomass stoves
Design
Analysis
Testing
Cookstove testing protocols

A B S T R A C T

Improving the thermal as well as emissions performance of biomass cookstoves has been of interest to researchers for a long time. Despite there being a vast literature on the subject, several technical issues remain unresolved with a variety of data and opinions being presented. The present article aims at bringing together literature spanning over three decades that addresses technical aspects of biomass stoves, *i.e.*, their design, analysis and testing. Literature on various design principles, features which determine the stove performance and different methods of performance prediction have been reviewed. Different cookstove testing protocols have been compared and various issues related to cookstove testing are critically discussed. The results of laboratory and field studies on cookstoves by various researchers are presented. Literature on health impact of cookstoves, their dissemination and adoption has also been included. The focus has been on critically analyzing the findings presented by various researchers over the past 3–4 decades in the backdrop of the advancement of the state of knowledge in the area. Wherever conflicting findings were encountered, efforts have been made to reconcile the same using the understanding of the fundamental phenomena.

Contents

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http://dx.doi.org/10.1016/j.rser.2014.09.003
1364-0321/

1. Introduction

Currently about 2.7 billion people in developing countries rely on biomass including wood, charcoal, tree leaves, crop residues and animal dung for cooking. The share of the population relying on biomass for cooking is highest in sub-Saharan Africa and India [1]. In India, nearly 66% of the population cooks food using different biomass fuels [2]. The situation is not likely to change in the near future due to the high cost of LPG that makes it unaffordable for poor people across the world [3–7].

The biomass burning devices used for cooking are known in the literature by various names such as *cookstoves*, *wood-burning cookstoves* or *biomass cookstoves*. Regionally, cookstoves are known by various names such as *chulha* in many parts of India, *Kang* in China, *Keren* in Indonesia, *Jiko* in Kenya. The traditional versions of cookstoves are highly inefficient and have high emissions leading to respiratory and other health problems. Despite these devices having such a wide usage and strong impact on the lives of the poor people, the design and development of these cookstoves have received relatively less attention from the scientific and technical community of the world. Consequently, despite a concerted effort by many groups at the grassroots level, the problem is still far from resolved. In the recent years, the technical challenges in the development of clean, efficient and also user-friendly cookstoves has received greater attention from the researchers leading to a new generation of cookstove designs, most of them using the gasification route with forced air supply as the fundamental design feature and many adopting thermoelectric generators for driving the air supply fans. These developments also have their own challenges. Design of cookstoves has slowly grown from being primarily an art with trial and error approach into a more scientific exercise, with clear identification of generic principles and mathematical modeling including the use of advanced tools like the finite element analysis and CFD simulation. Even testing of stoves is being recognized as an area which requires a sound scientific understanding for its effective use. Further progress in the field requires more scientists and grassroots level groups to join hands, learn from the past work and using scientific understanding of the problem provide a range of solutions that the user can choose from. A study of the literature related to stoves can provide valuable inputs in this endeavor.

The literature related to stoves is indeed very vast covering several aspects which may be looked upon in the following categories: (i) General articles creating awareness about the issues related to cookstoves from a lay person's perspective. This literature is specifically useful to non-technical audience including users, grassroots level workers and policy makers. (ii) Semi-technical compendia of cookstoves with their engineering drawings and construction details; and cookstove testing protocols. These are useful for the manufacturers and technical staff involved in stove testing and dissemination. (iii) Technical books, reports and articles looking at the processes in a cookstove and the principles of its design and testing from a scientific perspective. This literature is meant for the researchers involved in design and analysis of cookstoves as well as developing/improving the testing methods. (iv) Articles presenting the findings of the laboratory and field level performance tests on various cookstoves. This literature helps the designers as well as the dissemination agencies. (v) Specialised articles on the health and environmental issues related to usage of cookstoves. These are useful for the policy makers as well as those working in the area of environment and public health. (vi) Literature focused on dissemination issues of cookstoves, for which the policy makers and dissemination agencies constitute the main audience.

The present review article is largely meant for the technical researchers working on cookstoves for whom literature in categories (iii) and (iv) is of prime importance and hence this part of the literature has been given the maximum coverage in this article. However, no technical research on cookstoves can be meaningful unless the researchers have a strong appreciation for the other aspects enumerated above. Thus, the literature in the other categories has also been presented, though more in the form of compact capsules. The approach followed in this article has four distinctive features: (a) to consolidate the valuable information extracted from various studies spanning more than three decades in a structured format and a form easily understandable by even the uninitiated but potential technical researchers in this area; (b) to highlight the commonalities and conflicts in the findings of

different researchers. The authors have also compiled and plotted data on cookstove testing from various studies to get a comprehensive picture of the same; (c) to find scientific reasons behind the conflicting reports in the literature particularly in the area of stove testing, based on the authors' own understanding of the concerned phenomena; (d) to present the latest developments in the field related to the technical aspects in design, modeling and testing of cookstoves along with the challenges in the future research of cookstoves as perceived by the authors. While the latest research in the area has been presented all along, the relevance of the old literature has also been brought out in building the fundamental understanding of the phenomena in cookstoves as also in providing directions to some of the unresolved questions of today.

2. Evolution of cookstove designs

2.1. Primitive to advanced designs

From the open fires of prehistoric times [8,9] and three-stone fires, cookstove designs evolved into shielded fires [10], that paved way to development of *improved cookstoves*. The traditional cookstoves are characterized by low efficiency and high emissions. The design and dissemination of improved cookstoves with better efficiency and lower emissions has a long history of more than five decades [11]. In India, the first improved cookstove reported in the literature, *Magan Chulha* was developed in 1947 [12]. A historical overview of cookstoves across the world is presented by the two recent review articles [13,14].

In the 1980s, the improved cookstove movement picked up in several developing nations [15]. In India, National Program on Improved Chulhas (NPIC) was launched in 1982. Improved Cookstove programs were also implemented in many other south Asian countries [16] and eastern African countries [17].

Though a reduction in emissions was achieved in some of these cookstoves, this was an era when major focus in the development of improved cookstoves was on saving fuel wood to reduce drudgery and conserve energy. The cookstoves developed in this era were primarily natural draft cookstoves with little or no requirement of fuel preparation.

Parallel to these efforts, certain groups were at work all these years to gauge the impact of the emissions from the cookstoves on the health of the users, particularly women and children [18–22]. Their work highlighted the need for cookstoves with substantially cleaner combustion as compared to the traditional ones so as to reduce the health hazards emanating from them. They emphasized that just removal of the smoke from the kitchen using chimney only transferred the problem from indoor to outdoor and did not eliminate it. As a consequence, the beginning of 21st century has seen a quantum jump in the interest of the scientific community in addressing the issue of emissions from biomass cookstoves resulting in the development of what are called the *next generation* cookstoves or *advanced* biomass cookstoves with special features of forced supply of air and/or gasification of biomass to ensure cleaner combustion.

As a consequence, in 2011, *improved cookstove* programmes have been reported to be active in 160 nations worldwide [23]. Government of India launched a new program called National (Biomass) Cookstove Initiative (NCI) in 2009 for development and dissemination of advanced biomass cookstoves to about 160 million households [24], and a desirable roadmap for such a program was prepared by a few researchers in India for the Ministry of New and Renewable Energy [25]. At the international level, a Global Alliance for Clean Cookstoves has been formed which has identified the need for focusing attention of major combustion laboratories across the globe on the problem of inefficient combustion in cookstoves and aims at supplying 100 million clean cookstoves to the poor people worldwide through concerted efforts [26].

2.2. Literature on cookstove design principles

The diversity of cooking practices not just across the world but even within small regions supported an outlook for a long time that the cookstoves must be custom made according to local requirements and thus cookstove design cannot follow any general principles. Since the early 80s, some important publications appeared with a distinct approach of recognizing the cookstove as an engineering system and identifying some generic design features which could help in improving the performance of a cookstove [10,12,27,28,29]. They also served as compendia for the cookstove designs of those times, providing guidelines for their construction as well. The technical discussions in these compendia provide valuable insights into the phenomena occurring in a wood stove, and thus can be very useful for cookstove designers and the researchers in this area even today.

In 1982, a special issue of the *Proceedings of the Indian Academy of Sciences* addressing fundamental aspects of science of wood combustion and various principles of cookstove design and performance was published. The articles in this issue were later republished in the form of a book called *Wood Heat for Cooking* [29]. The article by Verhaart [30], the first of its kind, talks about design of cookstoves following the general principles of engineering design *viz*., identification of the user needs, explicit definition of product specifications and manufacturing instructions. This aspect was later reinforced and elaborated by Bussmann [31]. Verhaart [30] also provides valuable data on energy needs for chemical transformation of certain food items and of the four major cooking functions, *viz*., boiling, frying, baking and grilling. Referring to Krishna Prasad's work [32] in identifying similar dishes in different geographical locations, Verhaart [30] suggested that the perceived vast diversity of cooking needs the world over can indeed be met with a very limited number of designs. Interestingly, in the days when scientific development of cookstoves was still in its infancy, the author pointed out the important role of uniform size of fuel particles for good performance of a cookstove – something which is yet to find wide acceptance particularly in improved cookstove programmes in many developing countries.

Chaplin [33] presented guidelines on selection of materials for fabrication of the cookstoves, considering economic factors as well as material properties such as strength, stiffness, impact resistance, resistance to thermal stress and shock, formability *etc*. Various cookstove fabrication materials such as sheet steel, cast iron, un-fired or air dried clays, fired ceramics and cementitious materials along with their relative merits and demerits were discussed.

In 1985 a comprehensive review article by Krishna Prasad et al. [34] discussed several technical aspects related to cookstoves from identification of the main cooking operations to mathematical modeling of combustion and heat transfer. The authors highlighted that worldwide cooking in water or milk is generally a two phase process *viz*. boiling and simmering the food. The stove was considered as an engineering system identifying various phenomena taking place with detailed discussion on the processes of combustion and heat transfer in open fires as well as closed stoves and comparison of the model results with the experimental findings. The authors also discuss several issues on testing of cookstoves, which are discussed later in this paper in Section 3.

VITA published a book by Baldwin [35], which provides detailed information on various biomass fuels, cookstove design,

construction and testing. The basics of fundamental phenomena in a cookstove and statistical methods required by an experimentalist are presented in an easy to use form. The author strongly recommends use of statistical methods in the analysis of cookstove testing results – an important component in the process of cookstove design. This text can serve as a handbook for cookstove designers and researchers.

After the 80s, for almost two decades, no publication highlighting the design principles for a cookstove appeared. The work of Larry Winiarski, the inventor of *rocket stoves*, appeared in the form of 10 principles of designing a woodstove in an article in 2005 by Bryden et al. [36]. More recently, the book by Mukunda [11] has a chapter on *TLUD type gasifier stoves*. The importance of *superficial velocity* in the design of gasifier stoves has been emphasized. The author recommends that pelletization is required for efficient use of agro residues. This has a strong implication on design of stoves, since the size of the fuel to be used is a very important parameter in stove design.

Though the literature discussed above does not present a unique methodology for design of an improved cookstove, it helps the cookstove designer in following a systematic approach ensuring that all important aspects such as user needs, scientific fundamentals, safety and maintenance issues, manufacturability, cost and many others are given due consideration. The most important contribution of these texts has been to highlight the design features which have acquired a generic character and deserve to be discussed independent of any specific cookstove design.

2.2.1. *Design features of cookstoves*

Every technical researcher in the area of stoves whether engaged in developing new designs or in analyzing and evaluating the existing designs needs to understand the prime reasons why a particular stove performs better than the other. This section, which consolidates the wisdom contained in the above literature, primarily serves the purpose of providing an insight into the importance of every special design feature from a technical perspective. A certain design may incorporate one or more of these features, presented here.

2.2.1.1. Direct combustion versus gasification. In combustion cookstoves, solid biomass fuel burns inside the combustion chamber in presence of primary and secondary air, which together are in excess of the stoichiometric air requirement. The hot products of combustion transfer heat to the pot and then escape into the atmosphere. Cookstoves that gasify the wood (or any other solid biomass fuel) prior to combustion are referred to as gasifier cookstoves. These are generally cleaner burning alternatives to the combustion cookstoves and hence the gasification of biomass is being widely adopted as a feature in the latest designs.

Combustion of solid biomass fuel involves heating and drying of the fuel, pyrolysis of the fuel leading to the release of volatiles and formation of char, flaming combustion of volatiles and glowing combustion of char. Biomass gasification, on the other hand, is the process of thermo-chemical conversion of a solid fuel to gaseous fuel. At elevated temperature, biomass loses its moisture and is then subjected to pyrolysis, resulting in its decomposition into char and volatiles just as in combustion cookstoves. Since in gasifier cookstoves, the oxygen supply is kept limited, only a part of the volatiles and char are oxidized. The carbon dioxide (CO_2) and water vapor (H_2O) thus produced then flow over the remaining char at high temperature getting reduced to carbon monoxide (CO) and hydrogen (H_2). The resulting gaseous fuel is called *producer gas* [37]. This gas is burned to liberate heat in gasifier cookstoves. Due to combustion of CO and H_2 and some other small chain hydrocarbons, the combustion is much cleaner in gasifier cookstoves as compared to combustion cookstoves where volatile products of pyrolysis, which are long chain hydrocarbons, are not able to undergo complete combustion in the given environment. Several configurations of these cookstoves are being developed and disseminated. Gasifier cookstoves can be broadly categorized based on direction of flow of intake air as updraft, downdraft, cross draft and reverse downdraft or top lit updraft (TLUD) cookstoves. The gasifier cookstoves offer various advantages such as high efficiency ranging from 35% to 50%, very low level of emissions, uniform and steady flame with ease of flame control and requirement of less tending. Most of the gasifier cookstoves in the market today are of the forced draft type [38–41].

2.2.1.2. Material of construction. While the traditional cookstoves are generally made of clay, bricks or cement, many designers of improved cookstoves select metal as the construction material due to the advantage of low thermal inertia, easy portability and ease of incorporating several desirable features for improvement of performance. The most recent cookstoves known for high performance also use metals, with some of them resorting to the use of ceramics for the interior lining for better durability in high temperature conditions. A metallic body reduces the energy stored in the stove body owing to its light weight, but can result in higher heat losses from the stove due it its higher thermal conductivity. This could however easily be reduced by appropriately insulating the cookstove [42] thus ensuring higher combustion chamber temperatures. On the other hand, although mud/cement/brick structure is a poorer conductor of heat, a heavy stove body results in a major penalty of stored energy in the stove body.

A portable stove made completely of metal is also expected to have a long life of the outer body but a combustion chamber made of metal may not last long unless a high quality, fire resistant stainless steel is used. On the other hand, the stove with a metallic body but having a ceramic combustion chamber is likely to have a longer life. The fixed brick/mud stoves normally require frequent maintenance but without much cost and hence are very commonly used in poor households. The impact resistance of non-metallic portable stoves would be low.

2.2.1.3. Grate. The use of a grate generally improves the combustion quality and rate very significantly, due to improved supply of primary air under the bed and better contact of this air with the fuel. According to Gusain [43] use of grate improves stove efficiency by 3–5% points. The tentative estimate of power flux (ratio of output power of cookstove to the grate surface area) is given as 50 W/cm^2 for chimney stoves and 10–15 W/cm^2 for non-chimney stoves [10].

2.2.1.4. Features related to air supply. The air inflow into the combustion chamber in the form of primary or secondary air sustains the combustion process and hence is at the core of performance of the cookstove. Rate of inflow of air is one of the most important factors determining the efficiency as well as emissions from cookstoves. In a combustion cookstove, stoichiometric air is the minimum requirement to achieve complete combustion theoretically. However, since mixing of volatiles and air can never be perfect, some excess air becomes imperative for complete combustion and to keep the emissions low [35]. Operation at near-stoichiometric conditions with a small quantity of excess air results in high combustion temperatures leading to better heat transfer and hence higher efficiency of the cookstove. On the other hand, too much excess air could cause incomplete combustion and poor heat transfer to the vessel owing to reduced combustion chamber temperatures [43]. Thus there is an optimum level of air flow rate required for good thermal as well as emission performance of the cookstove.

In the case of the natural draft cookstoves, De Lepeleire et al. [10] recommended the total air requirement to be 1.6–2 times the stoichiometric air requirement. In these cookstoves, the design must account for this requirement by ensuring that the balance between the frictional losses and the draft through the cookstove results in the desired air flow rate. In a forced draft cookstove, the characteristics of the fan chosen take care of this requirement. As a result, the performance of a natural draft cookstove is much more sensitive to its dimensions than that of a forced draft cookstove. This is also one of the reasons why many improved natural draft cookstoves do not perform as well in the field as they do in the laboratory, if their fabrication to close tolerances is not ensured, as was experienced during NPIC [15]. Forced draft in cookstoves not only allows the right amount of air supply but also ensures better mixing and hence more complete combustion with a potential to have very low emissions.

In a combustion cookstove, the required air comes in two stages as primary and secondary air. Providing for secondary air supply in the combustion chamber design results in shorter flames, thus limiting heat loss to the surroundings. The ratio of primary to secondary air is therefore a very important factor in determining the thermal performance of the cookstove. The literature suggests that the stoichiometric supply of air for 1 kg of wood should consist of 2.7 m^3 of primary air and 2.3 m^3 of secondary air [10]. Krishna Prasad [44] discussed the dependence of primary and secondary air required for a biomass fuel on its chemical composition, characterized by the ultimate and proximate analysis, and presented the appropriate relations.

In the context of gasifier cookstoves, the air needed for gasification is often called the primary air or gasification air, and this is generally 25–30% of the stoichiometric air. The air needed to burn the producer gas thus formed is often termed as the secondary air or combustion air [45]. In most TLUD type gasifier cookstoves available in the market, secondary air is supplied through holes above the gasification region.

Preheating of primary as well as secondary air always aids in achieving cleaner combustion and higher temperatures in combustion zone thus enabling reduction in emissions as well as increase in efficiency. Swirl in the incoming air is found to distinctly enhance mixing in the combustion chamber and hence has a substantial impact in enhancing the cookstove performance with increased efficiency and reduced emissions.

2.2.1.5. Chimney. A chimney provides draft for suction of air into the cookstove, and to remove flue gases from the kitchen. While draft directly depends on chimney height, a larger diameter results in greater mass inflow of air due to a larger area and a reduced frictional pressure drop through the chimney. The mass flow rate of air induced through the chimney depends more on its diameter than its height [43]. For every cookstove configuration, the height and diameter of the chimney must be so chosen as to balance the chimney draft with the air required for combustion and the frictional pressure drop [10,46], resulting in its best performance.

2.2.1.6. Damper. A damper is used to regulate the chimney draft and hence the air flow rate through the cookstove and thus can substantially reduce the fuel consumption [43]. The damper design in cookstoves has been kept simple in order to keep the cost low and to enable easy maintenance. However, it has been observed that the simple arrangement of a metal plate as a damper has not been very user friendly: it is not easy for the user to find the right position of the plate damper for best performance of the cookstove; it resulted in burn injuries to the cook due to the metal damper becoming hot; consequently, many users have been found to discard the dampers, which resulted in drastic deterioration in the cookstove performance owing to too much excess air [35,47].

2.2.1.7. Baffle. A baffle is a constructional element generally provided in a multiport cookstove to restrict the passage and direct the air flow so as to improve convective heat transfer between the combustion gases and all the pots. It can also improve combustion in such cookstoves by restricting the combustion volume. Since the baffle itself can get very hot, it also provides for increased radiant heat transfer to the pots [10].

2.2.1.8. Thermoelectric generators. Forced draught cookstoves require electrical energy to operate the fan. Besides using a battery, some stoves use a thermoelectric generator (TEG), which produces electric power using the temperature difference between the hot combustion chamber and the surroundings. The electric energy so generated can also be used to charge a battery [41]. This is an advanced feature available in some of the latest stoves. Various researchers have presented their designs of stoves with TEGs which utilize waste heat from biomass stoves [48–51].

2.3. Improved cookstove designs

Hundreds of types of improved cookstoves have been developed across the world ever since the shortcomings of the traditional designs became known. The merit of revisiting the past literature presenting the old designs may not be readily evident. However, present authors have found that at times, some of the very promising designs of the past have gone into oblivion due to a variety of reasons. Besides, a few small changes in some of the old designs can result into a much better product. Thus, the researchers interested in exploring the world of cookstove designs will find the information provided in this section useful.

Cookstoves may be classified in various ways based on configuration, material, mode of biomass combustion *etc.* [14,46]. Most of these can be found in cookstove compendia published from time to time. Some groups working on the design and development of cookstoves have published the details of their designs in the form of reports or articles in technical journals, while some others have limited their work to development without making available the documentation of their work in public domain literature. The literature of the former category is presented in more detail in Section 2.3.1. The latter category is significant owing to the number and variety of designs contained therein, and these are presented separately in Section 2.3.2.

2.3.1. Designers' publications on cookstoves

Publications by designers of cookstoves are generally expected to contain information on two aspects: (i) the distinctive features of the product developed and (ii) the design process followed by the designer. All the articles found in the open literature from the designers cover the first aspect but only a few discuss the design process. The literature relevant to this section has been divided into two broad categories based on whether the cookstove presented by the designer is a combustion stove or gasifier stove. In the former category, the metal stoves are presented separately from the mud/brick/clay stoves since the design features in the metal and non-metal stoves are generally different.

2.3.1.1. Combustion cookstoves. Mukunda et al. [52] designed and commercialized cookstoves which required prepared, small-sized fuel, something that Verhaart [30] had strongly recommended. This class of stoves called *Swosthee* and *modified Swosthee* (each with more than one versions), were found to have thermal efficiencies of more than 40% – much higher than the typical

Table 1
Features of some gasifier stove designs available in literature.

S. no.	Stove, year, reference	General description	Thermal performance	Emission
1	*Downdraft* (co-current) *Gasifier Stove* (Forced draft) 1982 [29,30]	Supply of air through a pipe into throat of the oxidation zone.	Gasification efficiency: 85%. Gas temperature: 700 °C. FP: 2–7 kW.	Production of clean burning gas.
2	*Downdraft Gasifier Stove 1992* [76]	Gasifier reactor with two burners. Combustible gas produced in $\frac{1}{2}$ to 1 min.	Time for boiling 5 l of water at 9 °C: 12–15 min. η: 35%.	
3	*Rice Husk Gasifier Stove* (Forced draft), 2012 [77]	Downdraft: 13 W fan for gasification air supply. Maximum fuel consumption rate: 2 kg/h.	η: 18–25%.	Black carbon: 10–50 μg/m^3
4 and 5	*Updraft and Downdraft Gasifier Stoves* 2007 [75]	Natural draft, community cookstoves installed at residential tribal schools.	Saving of 50% fuel-wood and 35% cooking time as compared to traditional stove.	
6	*Institutional Gasifier Stove* (*IGS2*) (Cross draft type) 2005 [79,80]	Natural draft with a chimney. Slotted cylinder inside reaction chamber permits entry of primary air on one side and an exit of producer gas on the other side. gas burner with two pots. Fuels used: rice husk briquettes; wood chips; wood twigs and coconut shells. Starting time: 20 min.	η: 24–28%. FP: 4.7 kW.	Steady and smoke-free combustion.
7	*Commercial Gasifier Stove* (*CGS*) (Cross draft type) 2005 [78,80]	Natural draft, for small restaurants, precast cylindrical segments of brick lining, 1.1 m high mild steel chimney. Provision for three pots.	Highest η: 31.8%. FP: 8.4 kW.	Steady and smoke-free combustion.
8	*Domestic Gasifier Stove* (*DGS*) (Cross draft type) 2005 [80]	Natural draft, for small restaurants, use of two pots. Slotted cylinder inside reaction chamber; starting time: 20 min. Use of 1.1 m high mild steel chimney Fuels used: rice husk briquettes; wood chips; wood twigs; saw dust briquettes and coconut shells.	Wood chips consumption: 3.2 kg/h. FP: 3.6 kW. Average η: 25.9%.	Steady and smoke-free combustion.
9	*Inverted Downdraft Gasifier Stove* (TLUD) 1996 [81]	Natural draft, entry of primary air at the bottom of the stove and secondary air at the top above the charcoal bed. An unstable, partly yellow flame due to poor air–gas mixing. An annular burner using a gas wick developed for mixing the gas with air and burning it cleanly.	Fuel burn rate: 4–10 g/min. The gasification air–fuel ratio: 1.28. FP: 1.2–3 kW.	CO level 80 cm above the stove was 22 ppm.
10	*Wood-gas Turbo Stove* (TLUD) 2000 [40]	12 V, 3 W blower for supply of gasification and combustion air. The superficial velocity in the range of 1.7–6.2 cm/s. Satisfactory operation of stove for fuels with moisture content up to 30%.	Fuel burn rate: 4.6–11.3 g/min. FP: 1.15–2.83 kW. Efficiency with different fuels: peanut shell: 31% at 2.1 kW; wood pellets: 31.8% at 2.5 kW; coconut shell: 37.5% at 2.8 kW; palm nut shell: 33% at 2.5 kW; wood chips: 20% at 2.5 kW; coal: 24% at 2.4 kW.	
11	*Inverted Downdraft Gasifier Stove* [82]	Blower for air supply; fuels: wood chips, sticks, pieces of husk, coconut shell and about 10% pulverized material of any bio residue. The life of the stove: 2 years.	η: 25–35%; FP: 3–5 kW. Continuous operation for 2 h without tending.	Very low gaseous emissions.
12	*Rice Husk Gasifier Stove 2005* (TLUD) [39]	12 V, 3 W blower for supply of gasification and combustion air. 12 V, a high temperature blue flame due to clean combustion; stove can operate with remote burners also. Laboratory as well as actual cooking tests conducted.	Fuel burn rate: 1.5 kg/h. Operating time: 45 min.	Blue flame combustion of producer gas like LPG stove.
13	*Producer Gas Stove* (Natural draft) 2008 [83]	TLUD type stove, cylindrical combustion chamber of inexpensive local material with a refractory lining inside. Air control with a slotted plate and handle arrangement. The stove suitable for a wide variety of biomass fuels.	η: 26.5%; FP: 5 kW	Kitchen concentrations of CO_2: 18–20 ppm, CO: 1–3 ppm
14	*Oorja Stove 2010* (TLUD) [38]	Design specs: power: 3 kW; superficial velocity:0.05 m/s. Stoichiometric air–fuel ratio: 6. Primary air: 18 g/min and secondary air: 54 g/min. Use of 1.2 V, 1.2 Ah Ni–Mh battery for fan to supply gasification and combustion air. Combustion chamber volume: 0.6l.	Fuel burn rate: 9–12 g/min. Efficiency with different fuels. WC-η: 49.3% at FP: 2.3 kW RHB+WC-η: 49.3% at FP: 1.9 kW CS+WC-η: 53.3% at FP: 2.2 kW MP+WC-η: 49.1% at FP: 2.5 kW	CO (g/MJ) PM (g/MJ) 1.3 6 1 10

Table 1 (*continued*)

S. no.	Stove, year, reference	General description	Thermal performance	Emission
15	*Daxu Cook stove 2007* (TLUD natural draft) [86]	Insulated chimney,	SFC: 1.6–2.6 kg/h	Smoke: 0.21–0.39 g/kg fuel; CO/CO_2:0.011–0.039;
		Fuel: loose or compressed crop residue, wood *etc.*	FP: 2.2–3.4 kW	CO: 0.2–0.26 g/kg of fuel. Highest CO: 50.8 mg/m^3. Lowest CO: 1.9 mg/m^3
		Two hot plates for keeping pots. Another design with a boiler for supply of hot water and central heating arrangement.	η: 32–43%.	Avg. indoor CO concentration: 4.4–28 mg/m^3
16	*PHILIPS Woodstove* (TLUD forced draft) [41]	Stainless steel stove body with low thermal mass, ceramic combustion chamber. A long life brush-less fan to supply primary and secondary air. Use of thermo-electric generator for charging the battery which operates the fan.	Three times fuel efficient as compared to the three stone fires. Wood saving up to 55%.	Reduction in smoke to one-tenth and VOCs to one-hundredth as compared to three stone fires.

Note: FP: fire power or input power; η: efficiency of cookstove; SFC: specific fuel consumption; WC: wood chips; RHB: rise husk briquette; CS: coconut shell; MP: marigold waste pellets.

20–30% observed in most improved cookstoves of that time [53–56]. Mukunda et al. [57] carried out an extensive work on design and performance of a *powdery biomass stove*, an improved version of a traditional sawdust stove. This cookstove can be operated with a mixture of up to 50% non-powdery biomass in powdery biomass, and was found to have very low CO emissions, of the order of 10–20 ppm. Dixit et al. [58] developed a *single port* as well as *multi-port pulverized fuel stove* using a fuel block.

Another portable single pot metal cookstove, with an efficiency of about 30% was developed by Gusain [43] and was commercialized under the brand name *TARA*. Many versions of this cookstove were available and they became quite popular in the late 1980s in certain parts of north India. Later, two-pan versions of this cookstove, made of fired or baked clay and having a chimney, were introduced under *TARA 200* series.

Still and Kness [59] explained the design of a *rocket stove* which consists of a cookstove body, L shaped combustion chamber and a chimney constructed from tin cans. The combustion chamber and chimney are insulated and the pot is surrounded by an insulated metal skirt. Various types of rocket stoves have been designed by Aprovecho Research Center [60], out of which *StoveTech* is one of the most successful designs. Boy et al. [61] reported that provision of baffles to *plancha stove* resulted in the improvement in thermal efficiency of the stove by 12% and overall reduction in fuel consumption by about 39% as compared to open fires.

In the category of fixed and heavy cookstoves, one of the most successful designs in certain parts of south India has been a two or three pot cookstove called *ASTRA ole* developed at Indian Institute of Science, Bangalore [62–64]. The development of this cookstove was first documented as an internal report [65]. About 1.5 million cookstoves were disseminated during the period 1984–2003 [63].

There are some notable designs in the literature which showed very promising performance in the laboratory but there are no reports of their reaching the field. It may be worth considering some of these designs today for further development. The *experimental metal stove* by Vermeer and Sielcken [66] was reported to have a maximum efficiency of 55%, at 6 kW nominal power with no secondary air supply. Sulilatu and Krist-Spit [67] developed the *Tamilnadu metal stove* for cooking mid-day meal of school children, which was reported to have more than 50% efficiency at power levels ranging from 3 to 10 kW.

Development of a *CTARA stove* backed by a very detailed technical analysis and experiments with an electrical analog of the stove has been presented by Bhandari et al. [68]. This is a portable stove but uses metal as well as clay for construction. It was estimated that the radiant heat absorbed by the pot was between 10% and 8% and the remaining heat absorption was convective. Krishna Prasad et al. [69] and Hasan et al. [70] discussed the principles of a *downdraft cookstove* of 'J' type construction for clean combustion which was further studied in detail by Hasan and Khan [71]. The cookstove had a combustion chamber with a grate on the shorter leg of the J and a chimney on the taller one. A domestic downdraft stove, operating on natural draft, with a chimney height of 43–50 cm that can be operated at 4–5.5 kW with very low CO/CO_2 ratio in the flue gases was demonstrated. Some designs of heavy non-metallic cookstoves that were reported by their designers are those by Yuanbo [72], Sharma et al. [47], Kandpal and Maheshwari [73] and Panwar et al. [74]. Tables S1 and S2 in Appendix A provide information about different metal stoves and mud stoves of combustion type.

2.3.1.2. Gasifier cookstoves – technology of the future. The need for cleaner combustion in biomass cookstoves has led cookstove researchers to solutions based on biomass gasification technology. The gasifier cookstove designs available in the literature fall in the

following categories based on the direction of flow of the gasification air: updraft gasifier cookstoves [75], downdraft gasifier cookstoves [76,77], cross-draft gasifier cookstoves [78–80] and inverted downdraft (also called TLUD) or pyrolysing gasifier cookstoves [38–40,81–83]. The main features of each of these have been summarized in Table 1.

The downdraft gasifier stoves are cleaner burning, since the volatiles produced in the pyrolysis process crack into lighter components as they pass through high temperature zone of oxidation, resulting in very small amounts of tar. Verhaart [30] discussed the use of downdraft gasification in cookstoves, both in forced as well as natural draft modes. Xiansheng [76] developed the Biomass Domestic Gasifier Cooking Stove (BDGCS) system in China. The efficiency of this gasifier stove was found to be 35% with fuel burning rate of 4 kg/h. Belonio and Bhuiyan [77] developed a downdraft gasifier stove cum power generation device using rice husk as a fuel. Sutar et al. [84] developed a laboratory version of *downdraft gasifier cookstove* with a specially designed partially aerated burner. The thermal efficiency of the cookstove was about 35% at 5 kW fire power, and the gasification air–fuel ratio was about 1.6–1.9. Vitali et al. [85] reported a design of *natural draught rice husk cookstove*. Fuel burning rate of the cookstove was 1 kg/h and water boiling efficiency of the stove was about 18% at fire power of 4.1 kW.

Different versions of community size cross draft type gasifier stoves have been developed by Bhattacharya et al. [79]. The main advantages of these designs are that they have simple construction, operate on natural draft mode, use briquettes made from crop residues as fuel, and have moderate efficiencies of the order of 25%.

The gasifier cookstoves which became popular in the field are essentially those of the TLUD kind. In this type of cookstove, the biomass is lit at the top where a charcoal bed is formed and pyrolysis occurs below this bed. The primary air required for gasification is supplied at the bottom of the cookstove whereas the secondary air required for combustion is supplied at the top, above the fuel bed. The pioneering work on this category of

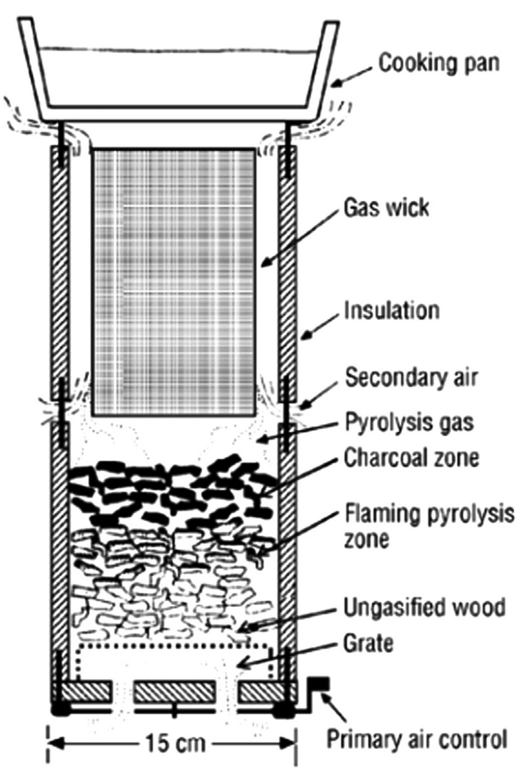

Fig. 1. Natural draught version of TLUD gasifier cookstove [81].
[Adapted with permission from Energy Sustain Dev 1996;3(2):34–7. Copyright 1996 Elsevier Ltd.]

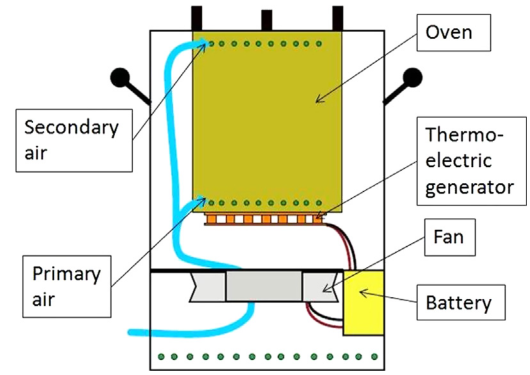

Fig. 2. Philips forced draught type cookstove [41].
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cookstoves was done by Reed et al. [40,81] who developed natural draft (Fig. 1) and forced draft versions of gasifier cookstoves, with efficiency values of 35–40%. Their measurements showed that primary air to fuel ratio varied between 0.75 and 1.59 for different power levels. The work on TLUD designs by Mukunda et al. [38] led to the commercial version of a forced draft cookstove called the *Oorja stove* with a reported efficiency of around 50%. Varunkumar [45] made detailed measurements on this stove and experimentally found that during stove operation, the value of primary air–fuel ratio was constant at 1.5 for different air flow rates. For most other TLUD stoves, measurement of primary air–fuel ratio has not been reported.

Another TLUD design called *Daxu cookstove* developed in China in 2006, is a clean burning cookstove [86,87]. Belonio [39] developed the widely acclaimed TLUD gasifier cookstove operating on rice husk. Anderson [88,89] discussed various designs of TLUD gasifier cookstoves popular worldwide. M/s Philips [41] have developed forced draft (Fig. 2) as well as natural draft versions of cookstoves. While the inventors of this stove did not state whether or not it is a gasifier stove, some researchers consider it as a TLUD type gasifier stove [90] and some others appear to treat it as forced draft type combustion stove [21].

San San Industrial Cooperatives (SSIC) in association with IIT Delhi developed a natural draft gasifier stove '*Paru*' [91]. This stove has a unique feature of pyrolysing loose biomass such as rice husk, groundnut shells, *etc*., in such a way that volatiles burn to provide heat for cooking as well as for sustaining the pyrolysis of the fuel. The char formed in the process is prevented from burning and hence can be used separately by briquetting as a clean fuel for other applications.

Out of all the articles on both combustion and gasification stoves referred to above, only four have described the process of design in detail: Belonio [39], Mukunda et al. [57], Still and Kness [59] and Sutar et al. [84]. Some information on design process of the Oorja stove is also available in Mukunda et al. [38].

2.3.2. *Compendia and other sources*

A glimpse of the variety of wood stoves in use in the western world in the 70s can be obtained from books by Larry [92] and Wik [93]. Many cookstoves developed in the 1970s and early 80s can be found in *Wood conserving cookstoves: a design guide* [27] and a *Woodstove compendium* [10]. In 1993, two compendia were published under Regional Wood Energy Program in Asia; one on Indian improved cookstoves [62] and the other on Chinese improved cookstoves [94]. The former document also includes the BIS cookstove protocol [95] while the latter presents similar information for Chinese cookstoves. A manual published by SAARC Energy Centre, Pakistan [16], covers various improved cookstove designs popular in

SAARC countries and details of their thermal and emission performance. The problems associated with dissemination of improved cookstoves and possible remedies have been discussed. It also covers commonly used cookstove testing protocols, *viz*., BIS [95], Water Boiling Test Protocol Version 3.0 [96] and Controlled Cooking Test Protocol Version 2.0 [97]. Details of commercially available *Thai cookstoves* are provided in a report along with procedures for mass production and dissemination of the efficient cookstoves [9].

In India, some Non-Governmental Organizations such as Appropriate Rural Technology Institute (ARTI), Technology Informatics Design Endeavor (TIDE) and Prakti have developed number of improved cookstoves which have been successfully disseminated. Some of the stoves developed by ARTI include *Improved Laxmi stove, Vivek sawdust stove, Sarai cooking system* (using charcoal*), Sampada gasifier stove* and *Bharatlaxmi stove* [98,99]. TIDE has disseminated technologies such as *Sarala cooking stove, bath water stove, industrial hot water stove and large cooking stove* [100]. More than 13,000 Sarala stoves have been disseminated. Prakti has developed a variety of cookstoves which operate using wood, charcoal and briquettes. These cookstoves are disseminated in India, Nepal and in many African countries [101]. The Energy and Resources Institute (TERI) has also developed gasifier cookstoves for use in community kitchens [75].

Envirofit International Ltd., a social enterprise established in Colorado, USA in 2003, works on the development and dissemination of improved cookstoves, primarily for the developing countries. They have developed wood as well as charcoal cookstoves of various capacities and have sold over 500,000 cookstoves worldwide [102]. Further information about cookstoves worldwide, including gasifier cookstoves can be found in the websites of Biomass Cookstoves Discussion Group [103] and HEDON household energy network [104]. HEDON also publishes a technical journal *Boiling Point* which discusses the issues related to cookstoves and household energy. ETHOS (Engineers in Technical and Humanitarian Opportunities of Service), a non-profit organization in USA, has been hosting cookstove conference annually since 2004. Presentations by various researchers related to designs of new cookstoves, testing results, protocols, dissemination of cookstoves at various parts of the world, *etc.* are available on the conference website [105].

A manual on improved cookstoves by Prasad [106] provides information on design features and construction of improved cookstoves. The details of some improved mud-brick cookstoves *viz. Sahyog, Thapoly, Dholadhar, Nada, Vikas* and *ASTRA Ole* have also been presented in the manual.

2.3.3. Improved cookstove designs – some insights

2.3.3.1. Combustion cookstoves – the strengths. Though the latest trend is towards forced draught gasifier cookstoves, the improved versions of natural draught combustion cookstoves have a few advantages from the users' perspective which include low cost, no moving parts and hence easier maintenance, low or no requirements for fuel preparation *etc*. Thus, combustion cookstoves can still not be considered as cookstoves of the past and hence it is relevant to summarise which features help in improving the performance of these cookstoves. The literature presented above shows that improvement in the thermal performance of different types of combustion cookstoves has been rendered possible by different factors as follows:

(a) In metal cookstoves, the improvement in performance is largely owing to one or more of the features such as a grate, holes for primary and secondary air with possibility of their preheating, promoting swirl, low thermal inertia and small sized fuel which enables operation at near stoichiometric conditions.
(b) The rocket cookstoves, on the other hand, are marked by simplicity of design, and have no provision for grate, secondary air within the cookstove or preheating of primary air. The improved performance seems to be achieved by restricting the combustion chamber volume and the primary air supply, improved mixing due to the 90° bend, lightweight construction with insulation and provision of pot skirt which allows the hot flue gases to rise up near the pot and enhance the heat transfer rate.
(c) In the heavy mud/ceramic cookstoves, use of grate, restriction of airflow using baffles or door for the combustion chamber, and additional features for mixing of air and fuel result in improved performance. However, high thermal inertia, with substantial heat absorption during the initial phase is a major drawback of these cookstoves. This can generally be offset, albeit only partially, by increasing the heat transfer surface area with the use of multi pot design.

2.3.3.2. Gasifier cookstoves – the challenges ahead. The major advantage of gasifier cookstoves is their substantially cleaner combustion and hence drastic reduction in emissions as compared to the combustion cookstoves of similar power rating. However, at the same time there are certain issues associated with such stoves, which must be addressed suitably by the scientific community as follows:

(a) They require small sized prepared fuel. If it is woody biomass, it must be cut into small pieces having dimensions of at most 2 cm. In case of powdery biomass, pellets or briquettes must be prepared so as to use them in gasifier stoves. Hence while supplying gasifier stoves, the manufacturer must specify the type of the fuel suitable for the stove and make arrangements to supply prepared fuel for the stove. Alternatively, the promotion agencies for these stoves must create a system for easy supply of prepared fuel to the user at a reasonable cost.
(b) The design of natural draft gasifier cookstoves poses special challenges. The pressure drop through the stove is the main governing factor for the amount of air supplied which in turn determines whether the stove will operate as a gasifier stove or not. Whether the stove has a chimney or not, the draft created due to buoyancy effect must be such that only 25–30% of the stoichiometric air enters the stove as primary air.
(c) Now-a-days most of the gasifier stoves available in the market are of forced draft type using battery operated or electrically powered fans. Some stoves (e.g. *Philips forced draft stove*) are provided with TEG. These accessories increase the initial cost of the stoves on one hand, and on the other hand, the need of electricity for charging the battery and the need to change the battery periodically add to the running cost of the stove. These factors also add to difficulties in maintenance in remote areas, and non-recyclable waste in the environment.
(d) Use of a fan reduces the variability of airflow into the stove and improves the control on air supply. However actual distribution of this air into primary and secondary streams is governed by the flow resistance in the path of primary air, which is mainly due to the fuel bed. Since the height of fuel bed is an operational variable, the primary to secondary air ratio can vary substantially during operation. This can result in the same stove being operated as a gasifier stove when the primary air is in the range of 25–30% of stoichiometric air or as combustion stove if the primary air fraction is substantially higher. This is possibly the reason for the *Philips forced draft stove* being referred to as combustion stove by a few researchers and gasifier stove by a few others.

3. Mathematical modeling of biomass cookstoves

While some researchers concentrated on developing new designs of cookstoves, some others focused on the analysis of these cookstoves through mathematical modeling of the phenomena with a view to understanding their physics and to enable prediction of cookstove performance. Mathematical modeling constitutes substantial part of the technical literature on cookstoves. Most efforts in the modeling literature if the earlier years have been limited to tackling the heat transfer and natural convection flow by using zero dimensional (or integral) form of the momentum and energy equations, with some differences in the assumptions made. More recently, the literature on CFD simulation of some stoves has appeared. While use of CFD packages is considered by some as the future of modeling of cookstoves, which can be a very important tool in developing the more optimal designs, the challenges in CFD modeling of cookstoves also need to be understood. Thus, this section presents literature on both types of models while highlighting the advantages and limitations of each approach.

3.1. Algebraic models of cookstoves

While this section is dominated by the literature of 1980s and 1990s, it is still relevant today since the fundamental approach used in these studies continues to be the basis of even some of the latest studies on cookstove modeling. Moreover, in certain aspects the advantages of this approach make this kind of modeling more attractive than the advanced techniques of CFD simulation.

3.1.1. Open fires

Bussmann [31] modeled the *open fire* plume to obtain analytical expressions for plume width, temperature profiles and gas velocities as a function of height. It was found that fire power does not affect maximum flame temperature but it affects the flame height which increases as (fire power)$^{2/5}$. Experimentally determined flame heights were comparable to those predicted by the model but velocity was under-predicted and temperature was over-predicted.

3.1.2. Closed cookstoves

3.1.2.1. Heat transfer models. De Lepeleire and Christiaens [42] presented a steady state model of heat transfer from a hot gas flowing between the pot bottom and cookstove wall or between shield and side wall of the pot. The model showed that insulation of cookstove walls improves heat transfer to the pot by about 30–40%. The effect of insulation of the pan lid was also simulated, the results from which showed trends similar to the experiments.

Krishna Prasad et al. [34,107] suggested a simple approach to calculate heat transfer through combustion chamber walls in a closed cookstove, using one dimensional transient heat conduction in a slab. The relative heat transfer performance of stove walls made of three different materials (dried clay, ceramic and metal) was determined. The model showed the ceramic cookstove to have best performance for the parameters selected. They also showed that radiation could be 1/5th to 1/3rd of the total heat input to the pan. No comparison between the quantitative model predictions and experimental measurements was presented.

A model for estimating heat transfer rate to the pot and hence the efficiency of a charcoal bucket cookstove has been presented in a report of Royal Forest Department, Thailand [9]. Using several simplifying assumptions, the water boiling efficiency of the cookstove was expressed in as a function of certain parameters, which were determined through linear regression of the experimental data available on 36 bucket type stoves.

Kohli [108,109] developed a simple algebraic model for heat transfer to the pot in a sawdust stove. The model used algebraic expressions with correction factors derived from CFD simulation. The results showed that in high power cookstoves, the attainable efficiency can be severely limited due to high Reynolds number and practical limitations on the size of the pot.

3.1.2.2. Fluid flow and heat transfer models. De Lepeleire and Christiaens [42] presented a model for air induction in a stove by natural convection by equating chimney draught to the pressure drop. Using this along with energy equation, the air flow rate and mean temperatures in the chimney were evaluated and the heat transfer to the pot was determined. The model predicted a sharp decrease in efficiency with increase in fire power. No comparison of the model results with experiments was reported.

Bussmann [31] adopted a similar model to analyze a shielded fire cookstove. The excess air factor and the efficiency were obtained as a function of pot-shield gap. The model was found to predict more rapid decrease of efficiency with increase in the pot-shield gap than that observed in experiments. Two possible reasons for this discrepancy were presented by Kohli [108]: (i) balancing only the frictional pressure drop with the buoyancy term neglecting acceleration term in the momentum equation (ii) use of relations valid for hydrodynamically fully developed flow for pressure drop. Both these assumptions could lead to over-prediction of mass flow rate of air through the system and hence under-prediction of efficiency at higher power.

The work by Date [110] on *CTARA stove* followed a similar approach but by dividing the entire cookstove into several control volumes. The predictions were found to match with the experimental results with the exception of power. The experimental results showed a negligible effect of power on efficiency, while the model results indicated an increase in efficiency with increase in power. One of the possible reasons for this discrepancy was identified as use of steady state model and neglecting sensible heat loss through the stove body.

The same approach of solving two equations, *viz*., one for momentum balance and the other for energy conservation, has been reported very recently for analysis of a rocket elbow stove by Agenbroad et al. [111]. The model was validated experimentally using two sizes of *rocket elbow stoves* with very good agreement for combustion temperature and excess air ratio. It was observed that at low fire power, the fuel mass flow rate suddenly increases but afterwards there was a decrease in mass flow rate with further increase in firepower. This phenomenon in natural convection stoves was also highlighted by Kohli [108,112].

Agenbroad et al. [113] modified the previous model [111] to develop its non-dimensional form for prediction of behavior of a natural draft biomass cookstove. The authors claim that this provides a major advantage of generalizing the behavior of all such stoves. The model was validated against experiments on rocket elbow stove, with as well as without a pot.

3.1.2.3. Combustion models. Verhaart [30] reported a simple model for combustion of a fuel in a counter flow configuration to understand relationship between power output of char and the volatiles. The pyrolysis was modeled by assuming constant fire penetration rate. The results showed that it was very difficult to operate such a cookstove at nearly constant power. According to the author the counter flow configuration was also not conducive to clean combustion since the volatiles would cool down before burning. No comparison of the model with experiments was presented.

Moerman [114] developed a mathematical model to predict flue gas composition for downdraft combustion process. The model predicted an optimal value of excess air factor for minimum CO/CO_2 ratio. Qualitatively, the same trend was observed in experimental

measurements as well. However, the predicted values of CO/CO_2 ratio were much lower than those observed experimentally.

Kausley and Pandit [115] formulated steady state and transient combustion models for a domestic cookstove, *Harsha*. The superficial velocity of air calculated using steady state model matched well with experimental measurements. The temperature in the fuel bed and the mass loss rate results of unsteady state model also showed satisfactory match with measurements.

3.1.2.4. Other models. Johnson et al. [116] have used *Monte Carlo* method for prediction of kitchen concentrations of PM and CO, based on cookstove emissions and kitchen characteristics. It was found that the modeled distributions of $PM_{2.5}$ and CO concentrations were highest for the traditional cookstove, with reasonable comparison with published data.

3.2. CFD and structural modeling of cookstoves

The latest trends in cookstove modeling involve use of CFD for thermal analysis and use of finite element analysis for studying the structural strength of the cookstove material. The literature on these aspects is rather limited, though it has been expanding in the past few years.

Kohli [108] carried out CFD simulation of buoyancy-induced fluid flow and heat transfer for the simplified geometry of a sawdust stove with a pot. The induced air flow rate was found to first increase with increase in volumetric heat release and then decrease. It was pointed out that at higher heat release rates, temperature in the system increases resulting in increased buoyancy causing higher induced velocities but at the same time decrease in density. Since the induced mass flow rate is a product of velocity, density and the area of the passage, this competing phenomenon results in a maximum mass flow rate of induced air at a certain power of the stove. The air flow rate was found to be a strong function of spacing between the stove and the pot, with flow separation at large spacing which had a strong bearing on the heat transfer to the pot.

Ravi et al. [117] reported CFD simulations of the fluid flow, heat transfer, pyrolysis and combustion in a *simple sawdust stove*. The pyrolysis model was a transient one, while the fluid flow, heat transfer and combustion were modeled assuming steady state. According to the authors it is useful to translate the results of detailed CFD simulations into a simple algebraic model which can be used as a quick tool to predict the performance of a given cookstove and also carry out design optimization for a given stove configuration.

Dixit et al. [118] studied the behavior of the *pulverized fuel stove* computationally by considering condensed phase in fuel block region and gas phase in port region. Temperature distribution and rate of movement of the pyrolysis front were found analytically by solving one dimensional unsteady conduction equation. The gasification and combustion phenomena in the cookstove were modeled computationally using a commercial CFD code. During combustion mode of operation, the computed and experimental gas phase temperatures were comparable whereas during gasification mode a significant difference was observed between the two. This difference was attributed to the faster combustion of hydrogen as compared to carbon monoxide, a phenomenon that could not be captured by the single step reaction model used in the work.

Mathur et al. [119], Bhati et al. [120] and Ganesh and Gupta [121] carried out analysis of a two pot cement cookstove, *Bhagyalakshmi*, using finite element modeling on ANSYS commercial software. The analysis showed that cracking of the bridge above the fuel port of the cookstove made of cement, a low tensile strength material, occurs due to thermal stresses, and it could be prevented by providing a recess in the bridge. The analysis also showed that the mass of the material below the second pot could be reduced without affecting the structural strength, and in turn reducing the thermal inertia as well as the cost of the stove.

Gupta and Mittal [122] and Gupta [123] reported computational analysis of a single pot cookstove, *Janta,* developed by Central Glass and Ceramic Research Institute of India. It was found that the fuel bed porosity has a significant influence on both primary and secondary air flow rates. Heat transfer to the pot was found to show a maximum for cookstove-pan spacing between 10 mm and 15 mm. It was also reported that the divergent portion of the combustion chamber of the cookstove increases total heat transfer to the pot significantly.

Varunkumar et al. [124] reported both experimental and computational studies on a *gasifier cookstove* using ANSYS CFX software. It was estimated that the radiation heat transfer from char bed was responsible for 6% of the total flaming mode efficiency of the stove. It was found both experimentally as well as computationally that the stove efficiency increases with increase in pot size. There was very good agreement between predicted and measured efficiencies at different pot diameters. It was shown that using finite rate chemistry showed a good match of predictions of CO emission with the experimental measurements, compared to fast chemistry model.

Ndiema et al. [125] studied the performance of a scaled down version of a *Kenyan cookstove* using wood and charcoal as fuels. The physical and chemical processes occurring during the combustion of a fuel and the chemical reactions responsible for the formation of pollutants were discussed in detail. A simplified CFD model of biomass combustion using commercial software, FLUENT was presented. The model accurately predicted formation of CH_4 but under-predicted formation of CO.

Urban et al. [126] reported use of commercial CFD software for locating the baffles in *plancha stove* for its optimum performance. The flow and heat transfer were simulated using CFD and the heat transfer to the pan was optimized using a genetic algorithm, working in tandem with the CFD model.

3.3. Challenges in modeling of cookstoves

3.3.1. Complexity of the phenomena

A cookstove is a complex system with several phenomena of pyrolysis, combustion, fluid flow and heat transfer closely coupled with each other, and the coupling is stronger for natural draught stoves. The equations governing the flow and heat transfer through the cookstove are the continuity, momentum balance and the energy conservation. In addition, the species equations and the reaction kinetics govern the combustion and heat release. The number of species participating in the combustion reactions can run into hundreds. The presence of radiative heat transfer due to high temperatures further adds to the complexity. In some designs, turbulence can also play a dominant role. Thus a cookstove is a highly non-linear system. Modeling so many coupled non-linear phenomena is indeed a major challenge.

3.3.2. Simple models versus CFD

In view of the above, most of the models presented in the literature use governing equations in integral (and hence algebraic) form with several simplifying assumptions and interestingly can still capture the dependence of certain parameters like buoyancy-induced airflow rate, combustion chamber/chimney temperature, efficiency and CO/CO_2 ratio on the design and/or operating parameters qualitatively. For getting a reasonable

quantitative agreement of such models with experimental results, generally there is a need to incorporate correction factors obtained from experiments or CFD simulation. In contrast, CFD models reduce the number of assumptions required and can help solve for local quantities such as velocity profiles, temperature gradients, pressure distribution *etc*. From these, the gross quantities of mass flow rate, fuel mass loss rate, heat transfer rate, efficiency *etc.* can be derived.

However, CFD models are also not without limitations. In predicting complex phenomena of turbulence and combustion, model assumptions and non-availability of accurate reaction mechanisms result in the predictions deviating from experimental data significantly. Relaxing some of the assumptions in a CFD model can improve the predictions but often at an enormous cost of computational time and/or storage requirements. Thus, accurate prediction of combustion and emissions from a stove using CFD is still a far cry. CFD models are several orders of magnitude more time consuming both in terms of setting up of the model and in terms of its actual computations, when compared with algebraic models.

3.3.3. *Utility of modeling*

Thus, modeling of cookstoves has still not reached a level where it can be used as a tool for stove design. The true utility of mathematical modeling of a cookstove would become evident if the model can help in carrying out a parametric analysis of the stove and finally identifying optimal dimensions of the stove of a given configuration. The algebraic models are more suitable for use in optimization routines, even though they have hardly been used in literature for this purpose. CFD simulations for a few input parameters may help in identifying some of the unknown input quantities and correction factors for the algebraic models, helping to make the predictions of the latter more realistic. A judicious blend of the two tools is therefore the best option available at the present time.

4. Testing the performance of biomass cookstoves

Evaluating the performance of a cookstove is an integral part of the process of developing improved designs. Methodology of evaluation of cookstove has always been a very contentious issue due to a large number of factors affecting the behavior of a cookstove. This section focuses on giving a broad outline of the various methodologies used in this context which would enable the reader to appreciate the challenges in this field presented in the later part – particularly the issue of detailed designing of testing protocols, minimizing uncertainties and making the laboratory testing results useful in determining the field performance of the cookstoves. It shall be brought out that even the latest developments have not answered some of the important questions in this area and hence there is a need for further research in the area so as to make the testing techniques commensurate with the latest developments in cookstove design.

In this regard, the suggestions given in the literature of the 1980s provides very useful directions. Hence, the literature of that time is reviewed highlighting their major contributions.

The performance of a biomass cookstove can be characterized in two categories *viz*. thermal performance and emission performance. Thermal performance is measured in terms of fire power or input power of the cookstove, specific fuel consumption, efficiency and turn down ratio, while emission performance is measured mainly in terms of emission ratios or emission factors of pollutants. Performance of biomass stoves shows a strong dependence on operation parameters *viz*., characteristics of the fuel used, sizes and types of pots used, the type of cooking process, the ambient conditions, the ventilation levels, *etc*. This gives rise to the need for precise definition of the various performance parameters on one hand, and on the other, it necessitates reporting of the operating conditions precisely, while presenting the experimental results. This is accomplished by standardization of testing protocols. This section focuses on literature on the performance parameters and testing protocols for measurement of thermal and emission performance of cookstoves in the lab and in the field. The issues pertaining to cookstove testing protocols arising out of the literature shall also be discussed in this section.

4.1. *Performance parameters*

4.1.1. *Thermal performance parameters*

The paper by Bhatt [127] appears to be one of the first published works to discuss the issues of cookstove testing comprehensively. The insightful article is a precursor to several features of performance testing as it exists today: it attempted precise definition of performance parameters; it formalized testing protocols and reporting methods, and mooted the idea of efficiency *versus* power characteristics of cookstoves; it addressed critical issues of energy budgeting which are pertinent even today, such as whether to include energy absorbed by the pot in useful energy or in the energy loss; it attempted statistical analysis of test results; it highlighted the importance of testing a stove using multiple protocols.

Some of the commonly used thermal performance parameters are discussed below.

4.1.1.1. Power. The term *fire power* is used by Baldwin [35] and Yuntenwi et al. [128] to indicate the average rate of energy release during the entire burn period. While the former considers fuel and its calorific value on as-received basis, the latter considered the "equivalent dry fuel consumption" with assumptions on moisture content and calorific value of char. This difference leads to very different values of calculated efficiency for the same test results.

Bussmann [31] identified several variants of fire power giving them different names as follows:

Nominal power: The nominal power for a batch testing process, in which fuel is added in fixed quantities at certain intervals of time, is the average rate of heat release considering the fuel mass loss during the interval *between fuel additions*.

Average power: Since in a batch process accumulation of charcoal in the fuel bed allows stove to operate for long after fuel addition is stopped, the term average power pertains to *the entire testing duration* from the start up of the cookstove till the point the water stops boiling.

Maximum power: It is the highest nominal power for which build up of fuel bed occurs without choking of combustion chamber with fuel in a closed cookstove.

Minimum power: The summation of convective, radiative and evaporative losses from the pot divided by the efficiency of the cookstove gives the minimum power required to keep the food simmering.

Design power: It is the highest nominal power that the cookstove can deliver under steady state operation.

Bussman [31] experimentally found that for open fires, the design power was about 70% of the maximum power. Bussman et al. [129] mentioned that a cookstove should be operated near design power for safe and durable operation. Interestingly, most of the researchers [56,66,67,130] use the term *power output* for the rate of energy released due to combustion of fuel, which is referred to as *power input to cookstove* by some other researchers

[38,131,132]. This indicates that Bussmann's definition of the power output is from the fuel and not from the cookstove.

4.1.1.2. Thermal efficiency and specific fuel consumption. Baldwin [35] uses the term *Percentage Heat Utilization* (*PHU*) in place of overall or first law efficiency used by Bhatt [127]. Bussmann [31] uses the term *efficiency* for the same quantity. The actual relation suitable for computing the *first law efficiency* varies with the way the test is performed.

Baldwin [35] also introduced the term specific consumption (SC) (also known as specific fuel consumption (SFC) in literature [21,128]), which is a variant of specific per day consumption (SDC) and specific task consumption (STC) both discussed by Bhatt [127]. It is defined as the grams of wood equivalent consumed per kg of water remaining in the pot at the end of a water boiling test. Bussmann [31] also uses the quantity specific consumption (SC) but with the denominator having the quantity of food cooked or the water equivalent of the food cooked.

Although SC is closely related to efficiency, it is a quantity that has its own importance. According to Jetter and Kariher [133], efficiency can be misleading as an indicator of performance because sometimes the cookstove may achieve high efficiency (in terms of energy absorbed by the pot) but produce more evaporation losses from the pot. Since such stoves would have high specific fuel consumption (SFC), the authors recommended SFC as a better indicator of fuel efficiency of the cookstove.

4.1.1.3. Turn-down ratio. Bussmann [31] also introduced another important parameter of cookstove performance, *viz*., *Turn down ratio* which is defined as the ratio between maximum and minimum power of the cookstove. According to Bussmann, the designer should aim at a turn down ratio of at least 6. Still et al. [134] tested 18 different stoves with 14 of them using solid biomass; it was found that turn-down ratios of all the solid biomass stoves varied from 2 to 4.

4.1.2. Parameters characterizing emission performance

Biomass combustion in cookstoves generally results in emission of several pollutants, which include carbon monoxide (CO), methane (CH_4), non-methane hydrocarbons (NMHCs), nitrous oxide (N_2O), oxides of nitrogen (NO_x), particulate matter (PM), black or elemental carbon (EC), organic carbon (OC) and organic matter (OM) [19,21]. The most commonly used parameters to characterize both stove emissions and the exposure levels have been presented by Ahuja et al. [135]. For the measurements required to characterize a stove the commonly used parameters are as follows:

***Emission factor* (g/kg or g/kJ)**: This is the quantity of a given pollutant emitted from a cookstove in grams per kg of the fuel burnt or per kJ of energy released. Generally emission factors have a strong dependence on the power at which the cookstove is operated.

***Emissions per task* (g):** This stands for the total quantity in grams of a given pollutant emitted during a given task of say cooking rice or boiling beans and the like. This can be determined from the emission factor in g/kg by simply multiplying the same with the total fuel consumption during the period of carrying out the task.

If the focus is on the exposure to the user, the relevant quantities are as follows:

***Instantaneous indoor concentration* (mg/m^3):** This is the estimated (space averaged) concentration of a given pollutant in an indoor kitchen (or a room) at a given instant. This depends on the Emission factor of the cookstove, the fuel burn rate and the air exchange rate inside the room (which in turn depends on the extent of ventilation).

***Equilibrium indoor concentration* (mg/m^3):** This is the estimated (space averaged) concentration of the pollutant in the room when the time elapsed since the start of the cookstove usage is considerably longer than the residence time of air in the room which in turn can be determined as inverse of room air exchange rate.

***Mean indoor concentration* (mg/m^3):** This is the mean value of the estimated (space averaged) concentration of the pollutant in the room during the entire period of cookstove usage. Thus, this quantity gives time averaged as well as space averaged values of the pollutant concentrations in the room.

Similarly, the ambient air quality can also be defined in terms of the concentration of a pollutant in a given region averaged over a given period. Table 2 gives the national ambient air quality standards for USA [136], India [137] and WHO air quality guidelines 2011 [138] for different periods of averaging.

***Air exchange rate of the room* (h^{-1})**: It is defined as volumetric flow rate of air (in m^3/h) through the room under steady state conditions per unit volume (in m^3) of the room. It can also be stated as number of times the volume of room air changes in an hour. It is generally determined by measuring decreasing CO concentration at different positions in the test chamber after

Table 2
National ambient air quality standards for USA, India and WHO guidelines.

Pollutant	USA [136]		India [137]		WHO guidelines 2011 [138]	
	Value	Unit	Value	Unit	Value	Unit
CO	9	ppm (8 h)	2	mg/m^3	–	–
	10	mg/m^3 (8 h)			–	–
	35	ppm (1 h)	4	mg/m^3	–	–
	40	mg/m^3 (1 h)			–	–
PM_{10}	–	–	60	μg/m^3 (annual)	20	μg/m^3 (annual)
	150	μg/m^3 (24 h)	100	μg/m^3 (24 h)	50	μg/m^3 (24 h)
$PM_{2.5}$	12	μg/m^3 (annual)	40	μg/m^3 (annual)	10	μg/m^3 (annual)
	35	μg/m^3 (24 h)	60	μg/m^3 (24 h)	25	μg/m^3 (24 h)
NO_2	53	ppb (annual)	40	μg/m^3 (annual)	40	μg/m^3 (annual)
	100	ppb (1 h)	80	μg/m^3 (24 h)	200	μg/m^3 (1 h)
SO_2	–	–	50	μg/m^3 (annual)	20	μg/m^3 (24 h)
	75	ppb (1 h)	80	μg/m^3 (24 h)	500	μg/m^3 (10 min)

Table 3
Summary of some cook stove testing protocols.

Particulars	VITA Protocol:1985 [141]	BIS protocol (Revised version 2013) [145]	WBT-3.0: 2007 (water boiling test) [96]	EPTP-2009 (emissions and performance test protocol) [150]	WBT-4.2.2: 2013 (water boiling test) [149]
Room conditions for carrying out test	Use of wind breaker around the stove to reduce air movement. Measurements of ambient temperature and relative humidity.	Room temperature 25 ± 5 °C at the beginning of the test, air of the test room free from drafts.	Room protected from wind with sufficient ventilation.	Conduct the test at room temperature when ambient water temperature lies between 4 and 30 °C.	Room protected from wind with sufficient ventilation.
Instrumentation	Stop watch, mercury in glass thermometer or digital thermometer up to 105 °C, moisture meter, insulated gloves *etc*.	Digital balance (capacity: 15 kg, LC: 1 g or capacity: 100 kg, LC: 10 g (for community stoves)), measuring jar 2 l, 5 l, thermometer (range: 0–100 °C, LC: $\pm$0.1 °C), moisture meter.	Stop watch, weighing scale (capacity: 6 kg, accuracy: $\pm$1 g), digital thermometer (LC: 0.1 °C), moisture meter, standard pots *etc*.	Stop watch, weighing scale (capacity: 6 kg, accuracy: $\pm$1g), thermocouple, moisture meter, standard pots *etc*.	Stop watch, weighing scale (capacity: 6 kg, accuracy: $\pm$1 g), digital thermometer (LC: 0.1 °C), moisture meter, standard pots *etc*.
Type of fuel, moisture content and size	Air dried wood with a uniform size of 3×3 cm^2.	Fuel (Kail/Deodar/Mango/Acacia Eucalyptus), with size: 3×3 cm^2 for family size stoves and 4×4 cm^2 for community stoves or prepared biomass as specified by the stove manufacturer; with 5 ± 1% moisture content (use of oven dried wood in the old version of the protocol).	Air dried wood, obtained from same source and uniform in size (2–5 cm in diameter); use of fuel with different moisture content suggested to study its effect on stove performance.	Standard fuels: Softwoods such as pine or Douglas fir with moisture content of 4–10% and size of roughly 1.5 cm^2 or uniform in dimensions.	Wood with high calorific value (20–21 MJ/kg), with size 1.5×1.5 cm^2 and moisture content 6.5–10% on wet basis.
Pot size and quantity of water	No mention of specific pot size but the details of the pot used must be given and the pot to be filled by water up to 2/3rd of its capacity.	A table provided giving size of the pot and quantity of the water depending on fire power of the stove.	Standard pots of 7 l or 3.4 l depending on stove design and fire power, quantity of water: 5 l in large pot or 3 l in small pot or 2/3rd of the capacity of non standard pot.	A table provided to decide the quantity of water depending on fire power of the stove and initial water temperature.	Standard pots of 7 l or 5 l depending on stove design and fire power, quantity of water: 5 l in large pot or 2.5 l in small pot.
Use of pot lid, stirrer	No use of lid. No use of stirrer.	Use of pot lid recommended but use of stirrer not mentioned (use of stirrer in the old version of the protocol).	No use of lid. No use of stirrer.	Use of foam insulation on top of water during high power tests but not during simmering phase. No use of stirrer.	No use of lid. No use of stirrer.
Test power and duration	High power till boiling of water and low power simmering for 30 min.	Constant power, no simmering, total test duration: one hour.	High power cold start and hot start till boiling of water and low power simmering for 45 min.	The average time of high power cold and hot start and simmering for 45 min.	High power cold start and hot start till boiling of water and low power simmering for 45 min.
Initial and final temperatures of water	Ambient to boiling point of water in the first pot (in case of multiport stove) during high power stage. While simmering, maintain the water temperature at 5 °C below boiling.	Initial temp.: 23 ± 5 °C, final temp. 95 °C in the first pot (in case of multiport stove).	Ambient to local boiling point of water in the first pot (in case of multiport stove) during both cold and hot start. While simmering, maintain the water temperature at 3 °C below boiling point.	Ambient to 90 °C for water in the first pot (in case of multiport stove) during both cold and hot start. While simmering, maintain the water temperature at just above 90 °C.	Initial temp.: 15 °C, final temp.: local boiling point of water in the first pot (in case of multiport stove) during both cold and hot start. While simmering, maintain the water temperature at 3 °C below boiling point.
Fuel feeding rate	Not mentioned	In case of continuous feed stoves: continuous fuel feeding at an interval of 6 min. In case of batch feed stoves: fuel feeding as recommended by manufacturer (in the old version: fuel feeding every 15 min).	Depending on the type of stove, fuel feeding may be batch or continuous type.	Stove manufacturer's specifications if provided, otherwise feed the fuel to heat the water rapidly during cold and hot start phases and use minimum amount of fuel while simmering.	Depending on the type of stove, fuel feeding may be batch or continuous type.
Calculation of stove thermal efficiency	Thermal efficiency was termed as percentage heat utilized (PHU). Neglected the heat absorbed by the pot(s). Considered the mass of water lost while boiling.	Consideration of heat absorbed by the pot (s) as well as heat released by kerosene while staring. Neglected the mass of water lost during heating. Neglected char remaining at the end of the test as the test continues till the end of visible flame.	Neglected the heat absorbed by the pot(s). Considered the mass of water lost while boiling. $C_{ch} \approx 1.5 \times C_{wood}$. $L \approx 12\%$ of $C_{wood.}$ Calculation of equivalent dry wood, to account for moisture in fuel.	Neglected the heat absorbed by the pot(s). Considered the mass of water lost while boiling. Calculation of equivalent dry wood, to account for moisture in fuel also considered the amount of energy required to evaporate fuel moisture.	Neglected the heat absorbed by the pot (s). Considered the mass of water lost while boiling. Calculation of equivalent dry wood, to account for moisture in fuel also considered the amount of energy required to evaporate fuel moisture.
Statistical analysis of stove testing results	Repetition of each test at least four times and statistical analysis of the results.	Not mentioned.	Discussion presented on comparison of performance of different stoves with the help of confidence level and *t*-test. Recommended repetition of each test for at least three times.	Brief discussion presented on test replicates and confidence level.	Discussion presented on comparison of performance of different stoves with the help of confidence level and *t*-test. Recommended repetition of each test for at least three times.

Table 3 (*continued*)

Particulars	VITA Protocol:1985 [141]	BIS protocol (Revised version 2013) [145]	WBT-3.0: 2007 (water boiling test) [96]	EPTP-2009 (emissions and performance test protocol) [150]	WBT-4.2.2: 2013 (water boiling test) [149]
Measurement of emissions	Not mentioned.	Hood method recommended with detailed dimensions of the hood and its accessories. Sensors for gas analysis also recommended.	Not mentioned.	Hood method recommended. Sensors for gas analysis also recommended.	Hood method recommended. Sensors for gas analysis also recommended.
Emission standards	Not mentioned.	CO should not exceed 5 g/MJ_d for both natural as well as forced draft stoves. TPM should not exceed 350 mg/MJ_d for natural draft stove and 150 mg/MJ_d for forced draft stove.	Not mentioned.	A single pan wood stove should not emit more than 20 g of CO and 1500 mg of PM (<10 μm size) during a complete test.	Grouping of stove performance in five categories from tier 0 to tier 4. For best performing stove (tier 4), high power CO and PM: ≤ 8 g/MJ_d and ≤ 41 mg/MJ_d respt. low power CO and PM: ≤ 0.09 g/min/l and ≤ 1 mg/ min/l respt.

Note: C: Calorific value, kJ/kg, ch: char, L: latent heat of vaporization, MJ_d: mega Joules of energy delivered. TPM: total particulate matter, LC: least count.

the cookstove or the burning fuel has been removed from the room, and taking the slope of the semi-logarithmic plot of the concentration with time.

4.2. *Cookstove testing protocols*

Testing of cookstoves in the laboratory has primarily involved water boiling tests (WBT). In 1980, Intermediate Technology Development Group (ITDG) brought out a detailed document discussing the philosophy of biomass cookstove testing and giving the procedure for testing of a cookstove in laboratory as well as in the field [139]. Subsequently, in 1982 Volunteers in Technical Assistance (VITA) carried out further work on the above to release a draft protocol as a provisional international standard [140]. These standard procedures were reviewed and accepted in 1985 by several groups working on cookstoves [141]. This document included detailed procedures for WBT as well as two supplementary tests *viz*., Controlled Cooking Test (CCT) and Kitchen Performance Test (KPT) to assess the cookstove under closer-to-real-life conditions of usage in a kitchen. Gradually other protocols for WBT also appeared, some of which covered emission measurements as well. The methods used for emission measurements are rather limited. However for thermal performance several versions of WBT protocols have been in use internationally, with some countries like India, China *etc*. having their own national standards [62,94]. Bond and Fierce [142] reported the development of cookstove testing protocols worldwide starting from 1980s till 2009. Kaisel [143] reported existing cookstove protocols developed in China, India and in some African countries. A summary of various protocols till date is also presented in two recent review articles [13,14].

4.2.1. *Testing protocols for thermal performance*

This section presents the most salient features extracted out of the detailed documents of five prominent protocols for testing the thermal performance (also see Table 3). It is intended that this section serves the reader with a concise compilation of technical details of all these protocols, since such a presentation is not found elsewhere in the literature.

4.2.1.1. VITA protocol (1985). Three levels of testing for every cookstove were recommended for the first time by VITA standards *viz*. Water Boiling Test (WBT), Controlled Cooking Test (CCT) and Kitchen Performance Test (KPT) [141].

The water boiling test (*WBT*) simulates common cooking procedures and is used for comparison of performance of different cookstoves. It estimates the fuel consumed for a certain class of tasks involving boiling process. In this protocol, testing at high as well as low power levels was proposed, a feature which has been retained till date by most protocols except BIS protocol. During the high power phase a standard quantity of water is heated rapidly from ambient temperature to boiling. During the low power phase, the water is maintained within 5 °C below boiling point over a 30-min period at the lowest possible power. The protocol also insists that the test must be repeated at least four times and results presented with statistical analysis.

The controlled cooking test (*CCT*) provides the estimates of fuel consumed by a given cookstove while performing a specified cooking task. The procedure for conducting this test depends on the food to be cooked, cookstove design and operation of cookstove. CCT is conducted in laboratory or in field demonstration centers by operators trained in preparing the food. This test can be used to compare different cooking practices on the same cookstove or for comparing the performance of a new

cookstove with the traditional cookstove under controlled cooking conditions. The protocol recommends repetition of same test at least thrice.

The kitchen performance test (*KPT*) is used to study the performance of a new cookstove in an actual household and the effect of its use on overall energy consumption. This involves measurement of fuel consumed by a new cookstove for a complete cooking cycle in the field. A minimum of five households with approximately same economic level are selected for the test. The recommended period for testing is five to seven days. It is also expected that the participating households use fuelwood for about 90% of their cooking needs. Due to the large efforts involved, it is suggested to perform KPT only after completion of a number of CCTs.

4.2.1.2. Indian standard on solid biomass Chulha-specification (IS 13152 (Part 1):1991). According to this protocol, at first the maximum burning capacity of a cookstove is determined through a preliminary test. Based on this, a set amount of oven dried fuel is taken so as to last the test duration of one hour. This amount of fuel is divided into four equal parts to be fed at 15-min intervals. A fixed amount of water is heated in a pot of specified size with lid until its temperature reaches 5 °C below the boiling point. Then this pot is replaced with a second pot with the same amount of fresh water. The experiment is continued till the visible flame dies down. This protocol is unique since it has guidelines for selection of various parameters for the test, such as the method of preparation of fuel, feeding rate, pot size and water quantity, size of hood *etc*. It also includes measurement of CO/CO_2 and total suspended particles (TSPs) [95]. One of the main weaknesses of this protocol is that it includes operation only at high power. Recently this protocol has been modified by the Ministry of New and Renewable Energy (MNRE), Government of India [144,145] to incorporate minor changes in the testing methods, and to include acceptance criteria for stoves of different types.

4.2.1.3. The water boiling test (WBT) (2003–2007):. Some drawbacks in the VITA protocol were identified by Still et al. [146]. It was modified for the Shell Household Energy and Health program by University of California-Berkeley and Aprovecho Research Center during 2003–2007. The final version of this protocol was labeled as WBT version 3.0 [96].

4.2.1.3.1. WBT 3.0. It was the first protocol to introduce a test which starts the cookstove at high power in hot condition. This is particularly useful in case of heavy cookstoves, taking into account the effect of heat retained in the stove from previous cooking session. Thus, the protocol involves operating the cookstove in three stages namely, high power cold start, high power hot start and low power simmering. During first two stages, the fuel consumed to boil a certain amount of water is determined whereas during last stage, the temperature of water is maintained at least 3 °C (and at most 6 °C) below boiling point. As pointed out by Still et al. [146], this would result in less generation of wasteful steam. The duration of simmering was also specified as 45 min in contrast to 30 min given in VITA [141]. This protocol also proposes the use of Student's *t*-test for comparing performances of two cookstoves. The revisions in VITA CCT and KPT were made by suggesting use of standard equipment during these tests.

4.2.1.3.2. Controlled cooking test (CCT version 2.0). This test is conducted using the similar procedure as given in VITA protocol for CCT [141]. The main difference between VITA CCT and CCT 2.0 is the calculation of equivalent dry fuel consumption wherein, the former neglects the energy lost in removing the fuel moisture content and the latter considers it [97,141].

4.2.1.3.3. Kitchen performance test (KPT version 2.0). This version of KPT provides extensive information on the criteria for selection of households and the procedure for conducting the test. The protocol suggests two stages of surveys; one for selection of households for the tests and second for actual fuel consumption measurements. It was suggested to cover at least 10% of all the families in the first stage survey. The second stage survey should be conducted about a month after distribution of new cookstoves. The measurement period should be 3–7 days [147].

4.2.1.4. ETHOS WBT protocol (2009). Engineers in Technical and Humanitarian Opportunities of Service (ETHOS), along with Partnership for Clean Indoor Air (PCIA), further revised the WBT 3.0, to evolve a new protocol called, WBT 4.1.2 [148]. Besides including all the three stages of WBT 3.0, it also provides instructions for emissions measurement and procedure for testing cookstoves using non-woody solid, liquid or gaseous fuels. Recently, a new version of this protocol designated as WBT 4.2.2 has been published in the website of the Global Alliance for Clean Cookstoves (GACC) [149]. This protocol enables graded evaluation of stoves as Tier-0 through Tied-4 based on their thermal and emission performance.

4.2.1.5. EPTP protocol (2009):. Some cookstove manufacturers (*Philips* and *ENVIROFIT*), in collaboration with Colorado State University and Shell Foundation, have developed a cookstove testing protocol called the Emissions and Performance Test Protocol (EPTP) [150]. This protocol emphasizes simultaneous measurement of the thermal performance with carbon monoxide and particulate emissions. Similar to WBT 3.0, EPTP consists of three phases of operation. The distinguishing features of EPTP are use of a floating layer of foam insulation on the surface of the water in the test pot to reduce vaporization; heating of water only up to 90 °C during the test; during simmering phase, maintaining water temperature close to 90 °C; and procedure for testing gasifier, charcoal and coal cookstoves without the high power hot-start phase.

4.2.2. Comparison of protocols for thermal performance

Several testing protocols are recommended by different groups in the literature, as summarized in Section 4.2.1 and Table 3. When one sets out to test a given stove using these different protocols, one gets different values of efficiency and emissions, thus giving rise to a dilemma on which result is more appropriate and why. In this section, the various differences between these protocols are critically discussed, with a view to identifying the causes for the non-uniqueness of their results. It is intended to scientifically analyze the different unresolved debates on various aspects of

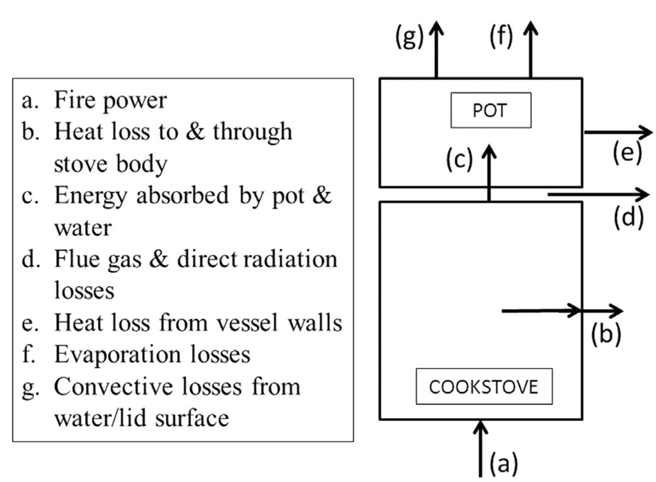

Fig. 3. Schematic of energy balance of a cookstove.

cookstove testing, so that the reader could get exposed to the physical principles underlying the different alternatives. It is thus intended to help the reader to make an informed choice of protocol for testing various aspects of a cookstove.

4.2.2.1. Energy budget of a cookstove. In order to physically appreciate the arguments in this section, it is necessary to understand the energy flow budget of a cookstove with reference to Fig. 3. Out of the energy released by the combustion of fuel (denoted by (a) in Fig. 3), a certain fraction (b) goes to the body of the stove, which is partially absorbed by the stove body, and partially lost to the surrounding atmosphere through the body. In stoves with a heavy material of construction, the absorbed part is the major fraction, while in lighter stoves the component lost to the surroundings is more significant. Net of this loss, the remaining energy goes towards the pot with its contents. Depending on the resistance offered to this heat flow by the pot and contents, a fraction of this energy (c) flows into the pot and its contents, and the remainder is lost to the surroundings, primarily as flue gas and direct radiation losses (d). If the pot has a significant thermal mass, then a sizeable fraction of this energy is absorbed by the pot walls, which otherwise can be neglected. The BIS protocol recommends explicit inclusion of the energy absorbed by the pot, while all other protocols neglect this term in calculating the numerator.

After the energy is absorbed by the pot and its contents, there are three avenues through which part of this energy is lost to the surroundings: Heat loss from the walls of the pot (e), evaporation losses of water in the pot (f) and direct convective losses to the surroundings (g) owing to the temperature difference between the water/lid and surroundings. While testing stoves, any factor that introduces higher uncertainty in any of these measurements could increase the uncertainty in stove efficiency, causing discrepancy between measured values in different tests. Besides, if the methods specified in the protocol result in differences in the physical phenomena related to any of the terms (a) through (g) above, this can also result in substantial differences in efficiencies between different protocols for the same stove.

4.2.2.2. Definition of thermal efficiency. Thermal efficiency may generally be defined as

$$\eta = \frac{\text{energy absorbed by pot and water}}{\text{energy released by combustion of fuel}}.$$

The two terms in this definition are calculated differently in different protocols, leading to differences in the values of thermal efficiency. In Fig. 3, the numerator corresponds to the term (c), while the denominator is denoted by (a).

In all protocols except BIS, the denominator of thermal efficiency is taken to be the product of lower calorific value of wood and the mass of "equivalent dry wood" used during the test. All these protocols also account for the charcoal remaining at the end of the test by subtracting the mass of charcoal multiplied by its calorific value from the denominator. It is important to note that the definition of equivalent dry wood is different in VITA, WBT 3.0, WBT 4.1.2 and EPTP protocols. In VITA protocol, mass of equivalent dry wood is defined as the as-received mass of wood minus its actual moisture content. In the WBT 3.0, WBT 4.1.2 and EPTP protocols, the energy required to vaporize the fuel moisture is also subtracted from the denominator. While EPTP protocol takes this quantity based on actual moisture content of the fuel, WBT 3.0 and WBT 4.1.2 assume the fuel moisture content to be 12% for this calculation. All these differences notwithstanding, the energy used for vaporizing fuel moisture will be less than 2% of the typical amount of energy released by the fuel in these tests, and thus the difference in the calculated thermal efficiency is not expected to be significant.

In BIS protocol, oven dried wood is used for the test and hence calculation of equivalent dry wood is not required. This protocol does not account for the charcoal remaining at the end of the test, with an argument that it is small in amount. However, it has been reported that accounting for remaining charcoal can increase the average efficiency value from 30.4% to 33.2% [151].

4.2.2.3. Uncertainty in stove testing. Uncertainty in stove testing is contributed to by two factors: instrument uncertainty of the measurements; and the uncertainty contribution owing to repeatability issues in measurements. Since the physical phenomena in a cookstove as well as boiling of water have several parameters that cannot be controlled in laboratory testing, the latter factor contributes substantially to the overall uncertainty in the results of cookstove testing.

Sutar et al. [151] conducted laboratory tests on an *advanced gasifier cookstove* according to WBT 3.0 and BIS protocols to address various aspects related to testing of biomass cookstoves *viz.* efficiency – fire power characteristic curve, end point of the test, final temperature of water, quantity of water, use of pot lid and fuel feeding rate. A detailed mathematical analysis was presented to explain the components of uncertainty in measurement of thermal efficiency and fire power of the cookstove. The results showed that instrument uncertainty contribution to the overall uncertainty in power as well as efficiency is very small as compared to the uncertainty due to repeatability issues. 99% of the uncertainty in stove power was contributed to by the test-to-test variation in duration of the test in WBT, while 91% of the uncertainty in thermal efficiency was owing to the test-to-test variation in evaporation losses.

L'Orange et al. [152] conducted water boiling tests using WBT 3.0 and EPTP protocols and found that EPTP protocol reduces uncertainty in results during testing of cookstoves (Fig. 4). Since uncertainties due to boiling are almost completely avoided in EPTP, this result is also in agreement with the findings of Sutar et al. [151].

4.2.2.4. Maximum temperature of water. One of the major differences between protocols is the maximum temperature to which the water is heated. When this temperature is close to the boiling point, nucleate boiling dominates the heat transfer mechanism on the inner surface of the pot, which results in heat transfer coefficients higher by two orders of magnitude compared

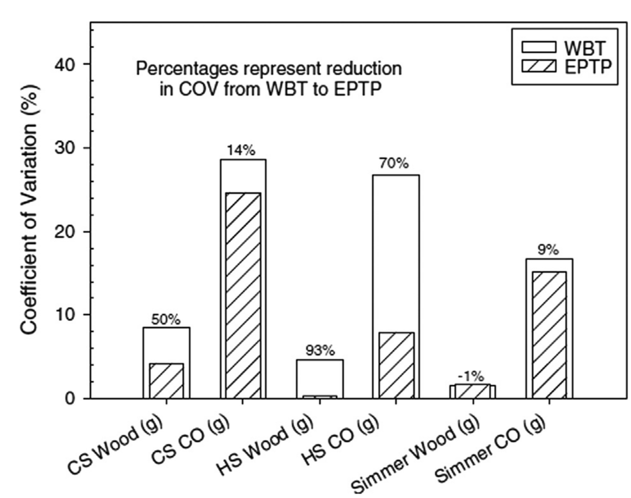

Fig. 4. Coefficients of variation for WBT and EPTP methods [150].
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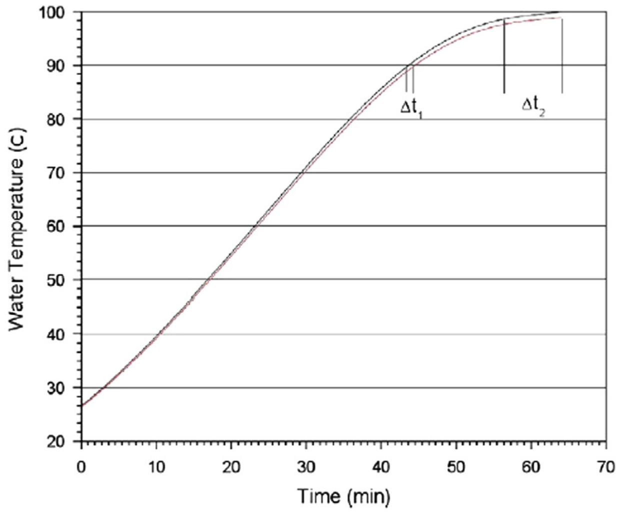

Fig. 5. Uncertainty in test duration due to variations in boiling point of water [150]. [Adapted with permission from Energy Sustain Dev 2012;16(1):3–12. Copyright 2012 Elsevier Ltd.]

to the case when nucleate boiling is absent, *i.e.*, at slightly lower water temperatures. If this happens, the fraction of heat entering the pot/water combination (c) increases, thus reducing flue gas losses, and resulting in better thermal efficiency. Since nucleate boiling dominates at water temperatures very close to the boiling point, even a decrease in temperature by about 2–3 °C can affect the efficiency substantially.

Thus, for a protocol which requires simmering temperature to be closer to the boiling point when the nucleate boiling has already set in, the heat transfer to the pot would be higher and so will be the thermal efficiency. Similarly, in the high power phase, a protocol like WBT 3.0 or 4.1.2 which requires the water to be raised to boiling point is expected to result in a higher thermal efficiency value than a protocol like BIS which requires water to be heated to a substantially lower temperature than the boiling point. This has been verified in the tests conducted by Sutar et al. [151] using the two protocols on the same stove. Thus, the maximum temperature of water in the test, both in high power phase and in simmering can significantly affect the test results. L'Orange et al. [152] reported that an uncertainty of 1 °C in measuring the boiling temperature of water can cause very high uncertainty in the measurement of total test duration (Fig. 5). Still et al. [146] pointed out that simmering at temperature which is only 0.5 °C below boiling point led to 56% more steam than simmering at 4.5 °C below boiling point. These observations clearly support the above explanation. BIS protocol specifies that a stirrer should be used to keep the temperature of the water uniform during the test. Although mixing due to convection homogenizes the temperature to some extent, stirring can help in reducing uncertainty in temperature measurement.

4.2.2.5. Use of lid on the pot. Another major difference between protocols is the use or non-use of a lid, and this is expected to have a multifold impact on the test results. Absence of lid results in increase of vapor loss (f) (Fig. 3) on one hand and on the other, increased heat transfer losses (g) from the water surface due to convective heat transfer from water to the ambient air. While the vapor loss term is accounted for in all protocols, the same is not true for the increased heat loss to the ambient air. Thus, not using the lid is expected to reduce the overall efficiency. Moreover, the fixed temperature rise required by a protocol in high power phase means that without a lid, the duration of this phase of the test will be longer than that with the lid. In some cookstoves, particularly the heavier ones, the duration of the test can have a strong bearing on the results of the test. In addition, if specific fuel consumption and time to boil are to be determined from the test, absence of lid is expected to result in higher values of both than those obtained with the lid. Gupta et al. [153] conducted laboratory experiments on conventional as well as improved two pot cookstoves using clay or aluminum pots and with or without lids. For both cookstove-pot combinations, use of lid ensured higher cookstove efficiencies.

In the BIS protocol, use of a lid with the pot is mandatory, while VITA, WBT 3.0 and WBT 4.1.2 specifically prohibit the use of the lid to avoid the error caused by the condensation of the water vapor on the interior of the lid. In EPTP, foam insulation is made to float on the water surface to work as a lid without the problem of condensation. However, no foam is used during the simmering phase, the reasons for which are not specified in the EPTP protocol.

4.2.2.6. Pot size and quantity of water. As the quantity of water in the pot increases for a given pot size, the area of the pot in contact with water increases, and this results in a larger area of heat transfer for the flue gases with water. Thus the term (c) increases (refer to Fig. 3) and term (d) decreases, resulting in an increase in thermal efficiency of the stove. This is generally expected due to the hot flue gases enveloping the pot sides resulting in heat addition to the pot from sides rather than heat loss (unless the pot size is very large). While the BIS and EPTP protocols specify the recommended sizes of pot and quantity of water for different fire power levels, WBT 3.0 and 4.1.2 specify two sizes of pots along with corresponding quantities of water as standards. These differences in specifications can result in significant differences in efficiencies obtained using these protocols.

4.2.2.7. Effect of ambient temperature. Another point of difference between protocols is the accounting for variation in ambient temperature during testing. While BIS specifies the ambient conditions for the test to be 20–30 °C, no other protocol puts any such restriction. EPTP gives a table for the quantity of water to be taken for different initial water temperatures varying from 4 to 30 °C. Although this is done to try and ensure that the total energy required by the water during the test is nearly the same irrespective of the initial water temperature, it must be noted that a low initial water temperature would generally correspond to a low ambient temperature as well, which will result in higher heat losses from the cookstove body to the ambient. Hence, at a lower ambient temperature the same cookstove is likely to give lower efficiency for the same fire power.

4.2.2.8. Issues related to fuel

4.2.2.8.1. Fuel quantity. It is important to note that only in BIS protocol, a fixed quantity of fuel chosen *a priori* must be consumed till the visible flame dies down to mark the end of the test. In all other protocols, a known quantity of water is taken through a fixed temperature rise marking the end of the high power test phase. This requires the fire to be extinguished and the remaining fuel (in the form of unburnt wood or charcoal) to be measured accurately so as to keep the uncertainties of measurements low. This poses problems in cookstoves which do not support intermediate addition of fuel or in those in which emptying of the cookstove in the hot state may pose a safety hazard (as in some gasifier and charcoal cookstoves) resulting in high uncertainties in determination of the net fuel used. For such stoves it may be more suitable to have a protocol which needs complete consumption of the initial fuel with at most a small quantity of charcoal left, as is the case in BIS protocols.

4.2.2.8.2. Moisture content in fuel. In the original version of BIS protocol, use of oven dried fuel was recommended. While this eliminated the need to account for the varying moisture contents in the calculations, it needs to be noted that excessively dry fuel may have different combustion characteristics than a fuel with about 10% moisture content. While this issue has not been investigated in the stove literature, it does merit a consideration. In the revised version of the BIS protocol, the desired moisture content of the fuel has been recommended to be $5\% \pm 1\%$. WBT 4.1.2 recommends moisture content of 6–10% while for EPTP, the figure is 4–10%.

4.2.3. Testing methods for emissions

The emission performance of biomass cookstoves is primarily measured using two methods namely a *hood method* and a *chamber method*. In case of a hood method, an extraction hood of appropriate shape to accommodate the largest possible cookstove to be tested is constructed above the cookstove. This hood is connected with an exhaust through a duct. A blower is fitted at the exit of duct to extract the burnt gases out of the kitchen or cooking place. Generally the height of the hood can be varied according to the cookstove height. Butcher et al. [55] discussed hood method for measurement of emissions in cookstoves. BIS protocol [95] provides detailed information on the dimensions of the hood used for estimation of emissions in cookstoves. The WBT protocols *viz.* BIS [95], WBT version 4.1.2 [148] and EPTP [150] present the procedure for measurement of emission performance of the cookstoves using hood method.

Ahuja et al. [135] and Gupta et al. [131] discussed the limitations of hood method such as the difficulty in accurate determination of air entrainment in flue gases; the possibility of change in the combustion characteristics of the cookstove due to the mechanically induced air flow caused by the blower; the physical interference by the hood with measurements and tending of the cookstove; and the high capital cost of installation of hood. Chamber method is an alternative to hood method.

In case of chamber method, a typical village kitchen room or any chamber constructed as per the experimental requirements can be used for testing of the cookstoves. The ventilation conditions inside the chamber are assumed to be constant over the period of measurements. The cookstove is kept in the chamber throughout the cooking cycle and the concentrations of pollutants are monitored inside the chamber. The emission factors of different pollutants are estimated using mass balance. Ahuja et al. [135] suggested the use of mixing fans to mechanically mix the air within the chamber. Ahuja et al. [135] and Gupta et al. [131] also discussed the limitations of chamber method: (i) the difficulty in maintaining the fuel burn rate and the ventilation constant over the period of time which is the main assumption for the chamber method; (ii) the operator has to expose himself to the smoke and pollutants while performing the experiment inside the chamber and (iii) the mixing fans used inside the chamber may interfere with the burning of the stove.

Johnson et al. [154] report measurement of CO and CO_2 using a constant flow sampling hood as well as a three-pronged probe placed directly above an open fire with a good agreement between the two methods. Thus, they suggest use of a simple probe for emission measurements both in the laboratory and in the field. Roden et al. [155] developed a mobile emission measurement system suitable for emission measurements in remote areas, capable of reporting optical properties of the pollutants.

The emission factors can also be determined by the carbon balance approach given by Wang et al. [156] in which all the burned carbon is assumed to be emitted into the atmosphere as carbonaceous particles and carbonaceous gases such as CO_2, CO, CH_4, and NMHCs.

Zhang et al. [157] developed the relations for predicting indoor CO concentrations and for estimating CO exposures and estimated CO concentrations as a function of time in a well mixed hypothetical village kitchen. It was reported that the air exchange rate affects the peak indoor CO concentration, the average CO concentration level and time for the CO levels to die down after the fire is extinguished. Increasing air exchange rate by building hoods or exhaust fans was recommended for removing pollutants. The reduction in daily CO exposure factor by 60, 55, 50, 26, 19, and 16 was estimated due to switching from charcoal, brush wood, dung, crop reside, coal, and fuel wood respectively to kerosene.

In 2004 non-governmental organizations, including Helio International, the World Wide Fund for Nature (WWF) and South-SouthNorth formed a certification standard for carbon offset, “The Gold Standard” [158]. The Gold Standard is a methodology for testing of improved cookstoves in the field [159–161]. According to McCarty, Gold Standard method is basically an extended KPT and is suitable for the developers of the projects that wish to secure carbon credits [162].

4.2.4. Recommendations on cookstove testing protocols

Design of a testing protocol is a very tricky task with two conflicting requirements; on one hand, the protocol must be able to give a fair estimate of the performance of a given cookstove under field conditions through laboratory level tests; on the other hand, it must also have the potential for high level of replicability for statistical acceptance and to enable comparison of results across laboratories as well as for different stoves. The latter requires the protocol to give precise specification of the parameters to be chosen during a test. However, the former requirement has led to some of the protocols keeping many parameters such as fuel feeding rate, pot shape and size flexible. Since these quantities vary in the field, not specifying these parameters builds in the real life variabilities in the testing process. However, this may not only hamper the replicability of the test but also make the comparison of different cookstoves tested by different groups very difficult.

The issue of characterizing the performance of the stoves realistically was raised by Krishna Prasad et al. [34]. They pointed out the inherent difficulties associated with trying to have a testing protocol which will simulate the cooking process realistically and will also be repeatable in the laboratory. They advocated that in place of a single efficiency value, cookstove performance can be better characterized by a plot of efficiency *versus* power generated using carefully designed water boiling experiments in the laboratory with high level of repeatability. They also showed that using simple analysis and these characteristics curves, it should be possible to estimate the fuel consumption for a specified cooking operation, without making the individual test procedure akin to the actual cooking process. Thus, according to them, the main objective of a cookstove testing protocol should be the generation of a set of cookstove performance curves for various operating conditions with high replicability.

The limitation of a single number of efficiency for characterizing a cookstove was also highlighted by Claus and Sulilatu [53] and Johnson et al. [154]. Johnson et al. [154] have brought out the discrepancy between the results of laboratory level WBTs and field level KPTs. They linked the power variation in an actual cooking cycle in the field to the combustion efficiency and profile of emissions rate with time. Thus, they suggest measurement of $CO_2/(CO+CO_2)$ ratios in the field to extract the typical burn cycle and then using similar fuel type as in the field to reproduce the same combustion efficiencies and emission rate profiles in the laboratory.

The suggestions of Johnson et al. [154] are a step forward towards linking the laboratory measurements with the field performance. However, the present authors see a few difficulties in this approach. Firstly, in the measurement of the combustion efficiency using $CO_2/(CO+CO_2)$, the variations in CO are likely to get camouflaged due to a very small value of CO as compared to CO_2. This, coupled with the sensitivity of the emission rate to local disturbances, the inherent variabilities in the combustion phenomenon and the measurement uncertainties will make it difficult to capture the burn cycle variation through these measurements with reasonable accuracy. Secondly, to reproduce the variation in these quantities with time in the laboratory may also be a very difficult task and is likely to require a lot of trial and error. While the authors [154] report that $CO_2/(CO+CO_2)$ ratios were found to correlate well with the combustion efficiency, the paper does not mention how the latter was measured. The uncertainties associated with CO and CO_2 measurements are also not documented. In the absence of these, it is difficult to ascertain the effectiveness of this approach in capturing burn cycle information in the field for reproduction in laboratory experiments.

The following enumerates the recommendations for consideration in future cookstove testing protocols:

(a) Cookstoves efficiency as well as emissions must be tested in the laboratory for different power levels so as to develop stove characteristics.
(b) The methods for these tests must give prime importance to repeatability and reduction in uncertainty which requires that
  (i) various operating parameters like fuel characteristics, fuel feeding rate, pot shape and size, quantity of water *etc*. must be defined precisely,
  (ii) water must be heated to final temperatures at least 5 °C below boiling point to minimize uncertainties associated with quantity of water vaporized as well as measurement of boiling temperature,
  (iii) a lid must be used on the pot to reduce uncertainty associated with vaporization of water and the heat loss from water to surroundings due to convection,
  (iv) for gasifier or combustion stoves with one time fuel feeding, the end of test must correspond to complete consumption of the fuel so as to reduce uncertainty in determining the mass and calorific value of the remaining fuel, which would be a mixture of virgin fuel, char and ash,
  (v) the tests must be conducted under ambient temperatures controlled within a narrow range, and
  (vi) detailed statistical analysis and uncertainty reporting must form an essential part of any new protocol, so that data reported in the stove literature becomes easier to interpret.
(c) The relationship between the characteristics developed in the laboratory and actual burn cycle in the field can be established through simple modeling. This can help in predicting the field level performance of a cookstove on the basis of laboratory measurements.

5. Results of measurement of cookstove performance

There is a large body of literature available on performance measurement of various cookstoves. The focus in this section is to compile this information classified under laboratory and field test conditions, so as to present a coherent picture that emerges from the literature. Owing to the large variety of test methods and different styles of reporting, such a compilation can help in forming an opinion on different classes of cookstoves, and the effects of design parameters and operating conditions on cookstove performance.

5.1. Cookstove performance in laboratory

Measurement of cookstove performance in laboratory has distinct advantages over measurements in the field. Certain factors such as ambient conditions, fuel type and moisture content are much in the control of the researcher. At the same time sophisticated measuring instruments are readily available in the laboratory. Various researchers around the world have tested different types of cookstoves in the laboratory. A brief summary of this is tabulated in Table S3 of Appendix A. These measurements can provide pointers to two different aspects of cookstoves: (i) Quantification of the effect of several design features and some operating parameters, which have been discussed in a qualitative and conceptual framework in Section 2.2.1. (ii) The relationship between performance parameters of power, efficiency and emissions. To bring out these aspects, an effort has been made in this section to synthesize the information from several studies – some of them reinforcing each other and some others contradicting each other with the help of a scientific analysis.

5.1.1. Effect of design features

5.1.1.1. Cookstove material. While the traditional cookstoves were found to be generally made of clay, bricks or cement, many designers of improved cookstoves selected metal as the construction material due to the advantage of low thermal inertia, easy portability and ease of incorporating several desirable features for improvement of performance. The most recent cookstoves known for high performance also use metals, with some of them resorting to the use of ceramics for the interior lining. The performance of these stoves as compared to the heavier mud/brick stoves is of specific interest to all cookstove designers.

Mukunda et al. [52] reported the design of metal cookstoves of very low thermal mass, *Swosthee*, with very high efficiency. Still et al. [134], while testing 18 cookstoves found that light weight stoves with rocket type combustion chambers emitted less PM as well CO as compared to three stone fire. In the studies of Claus and Salilatu [53] a heavy metal stove gave slightly better efficiency as compared to *Nouna*, a brick stove and *Tungku Lown*, a mud stove, but its emission performance was worse than that of the brick stove. Out of the five cookstoves tested by Ballard-Tremeer and Jawurek [54] the efficiency of *one pot metal stove* and open fire with grate (also called the *improved open fire*) were nearly same but metal stove had much higher emissions than the other cookstoves including a heavy *ceramic stove*. The two pot metal stove was found to have lower emissions than the one pot metal stove.

McCracken and Smith [163] found that *Plancha stove*, which had a metal firebox with kinder blocks and red bricks, had nearly same efficiency and substantially lower emissions than a three stone fire. Venkataraman and Rao [164] found that the metal cookstove tested by them had higher efficiency but nearly the same emissions as compared to the heavy cookstoves.

The above findings show that although light weight of the cookstove has the potential for improved performance, an ill-designed metal cookstove can be inferior to better designed heavier cookstoves in terms of emissions. However, it must be emphasized that in carefully designed cookstoves, light weight of metal cookstoves can be used to a distinct advantage. It is noteworthy that single pot metal cookstoves, if well-designed, can give efficiency of 40–50% while in the heavy cookstove category such values are attainable only with 2–3 pots even when the cookstove is carefully designed with several features to enhance the performance. This is supported by measurements of Claus and Salilatu [53] indicating that heavy mud or brick cookstoves absorb 30–40% of the heat during the cooking period, a part of which may get utilized in the next cooking cycle or for

water heating in the post cooking session. However, this utilization of accumulated energy is not taken into account for efficiency calculations in all cookstove testing protocols and hence does not get reflected in the test results. Considering the duration of about an hour of a typical cooking cycle and also the tests, the stored energy in a heavy cookstove will form a substantial part of the total energy released during the cooking or test period.

5.1.1.2. Grate. As mentioned in Section 2.2.1, grate has been widely recognized as a very important feature to enable better mixing of volatiles and primary air, and hence essential for enhanced performance. Bussmann et al. [129] found that for the open fire with grate a periodic steady state was established, which was not the case with the open fire without grate. Ballard-Tremeer and Jawurek [54] reported an increase in the efficiency of *open fire* from a range of 11.6–16.8% to a range of 19.7–23.1% along with reduced emissions of CO and TSP with the use of grate. Out of the five cookstoves tested by them *open fire* with grate had the least emissions, but a low range of operating power due to the grate size. Bussmann [31] and Bussmann et al. [129] reported that the introduction of a grate is found to reduce the fuelbed surface area required to generate the same power output, thus resulting in considerable fuel savings. The provision of grate was also found to increase the turn down ratio.

Dunn et al. [165] found that the *Thai charcoal stove* with small values of aperture area, grate porosity and pot-fuelbed distance was about 39% more fuel efficient than the cookstove with the larger values of these parameters. A report published by Royal Forest Department, Thailand [9] presents laboratory test results of 36 types of charcoal bucket cookstoves, 39 types of wood stoves and 5 types of rice husk stoves commonly used in Thailand. With increase in grate to pot distance, considerable change in efficiency of a *Thai wood stove* was observed. The efficiency of *Astra Ole* was also found to improve with an optimal grate-to-pot distance [64].

Interestingly, despite recognition of the importance of grate as early as in 1981 [10], some of the very successful cookstove designs in use today like many *rocket stoves* and the *Philips forced draft stove* do not use a grate. The L-shaped passage in rocket stoves favours mixing even in the absence of grate, while the use of forced draft is the feature that helps in better mixing in the *Philips* stove.

5.1.1.3. Air preheating, swirl and secondary air. The role of preheating, tangential entry or use of swirling devices for incoming air in improving the cookstove performance have been clearly established by Mukunda et al. [52] and Bhandari et al. [68]. Vermeer and Sielcken [66] also show improvement in efficiency of a metal cookstove from 40.3% to 43.4% due to preheating of air. Bussmann [31] highlighted the importance of secondary air holes in a *shielded fire*, whose efficiency declined drastically from 51% to less than 40% with the closure of secondary air holes. In contrast, Dirks [166] reports that no clear influence of secondary air was observed on the efficiency or power output of an *experimental metal stove* with chimney. It is likely in the latter case that chimney provided primary airflow high enough for complete combustion, rendering the secondary air unimportant.

In *CTARA stove* introducing perforations in the inner cylinder drastically reduced smoke due to better mixing of secondary air [68] and probably also due to its preheating. A series of such measures improved the efficiency of *CTARA stove* from about 26% to about 47%, with a very marked contribution of tangential entry of air and swirling devices [68]. Kumar et al. [64] report that the efficiency of *ASTRA Ole* could be increased from 16% to 47.5% with the use of optimal port sizes for primary and secondary air and other features. Claus and Salilatu [53] reported a distinct increase in cookstove efficiency with control of excess air using dampers.

5.1.1.4. Insulation. Use of insulation in *Astra Ole* increased gas temperatures and hence improved the cookstove efficiency from 42.7% to 45.7% [64]. Claus and Salilatu [53] found that the use of a 2 cm thick glass wool insulation around a metal cookstove resulted in 22% reduction in the heat loss to the environment and 13% increase in heat absorbed by the pots. De Lepeleire and Christiaens [42] estimated mathematically that replacing a 0.5 mm thick aluminum lid with a 3 cm thick wooden lid will reduce the heat loss from about 700 W/m^2 to one third of its value. The authors confirmed mathematically as well as experimentally that the insulation of pot lid is more effective in improving heat transfer to the pot than insulating the cookstove wall.

5.1.1.5. Chimney. Hasan and Khan [71] carried out a detailed study of the effect of chimney height on quality of combustion and cookstove power in a *downdraft stove* and found an optimal chimney height for minimum CO emission. Sulilatu et al. [67] reported that in *TamilNadu metal* stove, reduction in chimney height from 2 m to 1 m decreased cookstove efficiency from 48% to 40%.

5.1.1.6. Baffles. Heeden et al. [130] found that introduction of baffles in a *Nouna* stove improved its efficiency from 17.3% to 24.9% (by 7.6% points). Baffles helped in a similar manner in *Astra Ole* as well [64].

5.1.1.7. Forced draft and gasification. Through extensive tests on several stoves, Still et al. [134] found that in case of forced draft stoves improved mixing causes high combustion efficiency which results in very low PM and CO emissions as compared to three stone fire. MacCarty et al. [167] reported performance tests on 50 biomass cookstoves using the WBT 3.0 and a portable emission monitoring system (PEMS) to monitor CO and PM. As compared to three stone fire, five types of forced draft stoves showed average decrease in fuel consumption of 40% and decrease in PM emission by 90%. The corresponding numbers for rocket type cookstoves were found to be 33% and 46% respectively. According to the authors, the PM emissions can be reduced by thorough mixing of air, by ensuring sufficient draft throughout the cookstove and by complete combustion of fuel. Some of the more recent studies on several cookstove–fuel combinations have shown that the *Philips forced draft stove* gives much better thermal performance and low emissions as compared to natural draft cookstoves [21,90,133]. MacCarty et al. [21] reported performance of five biomass cookstoves, Jetter and Kariher [133] tested 14 cookstove–fuel combinations (10 biomass cookstoves and five fuels). While it is possible to use forced draft design in combustion as well as gasifier cookstoves, it has been found that almost all forced draft cookstoves available in the market today are also gasifier cookstoves. As discussed in Section 2.3.3, *Philips forced draft stove* is considered to be a gasifier stove by some researchers and a combustion stove by some others, while the designers of the stove are silent on this issue.

It has also been found that gasifier cookstoves are distinctly superior to combustion cookstoves resulting in much lower emissions. Some of the gasifier cookstoves are also natural draft cookstoves. In general combination of forced draft and gasifier mode of operation has been found to give good overall performance [38–40].

5.1.1.8. Other design features

5.1.1.8.1. Stove-pot spacing. In natural draft cookstoves, the spacing between the pot and the cookstove can have a strong effect on the air flow rate and hence efficiency as well as emissions. Bussmann [31] reported that in a *shielded fire*, there exist optimum values of pot-shield gap and pot-bottom gap for

best efficiency. At smaller spacing, insufficient supply of air results in poor combustion and hence increases CO/CO_2 ratio. This happens because a small spacing becomes the main resistance to the induced air flow and hence does not allow adequate air for combustion, while at very high spacing, excess air reduces the combustion chamber temperature and hence the efficiency reduces with increase in emissions.

5.1.1.8.2. Working height. Kandpal et al. [168] reported that a person standing in the kitchen with cookstove on the floor, will be exposed to a much higher levels of CO than a person sitting in the kitchen. The authors suggested well ventilated kitchens for the use of cookstoves without chimney.

5.1.2. Effect of operating parameters

5.1.2.1. Fuel type. According to Bussmann [31] and Bussmann et al. [129], wood species strongly affect the mass loss rate of the fuel as well as the maximum volatiles power for open fires. Venkataraman and Rao [164] found that the fire power of four cookstoves including metal and heavy cookstoves was almost independent of the type of fuel used, *viz*. wood, dung-cake and bio-fuel briquette. Ndiema et al. [125] reported that in a scaled down version of a *Kenyan cookstove* using wood and charcoal as fuels, less NO_x was emitted from combustion of wood as compared to charcoal. Maximum smoke densities of 80% and 40% were measured during combustion of wood and charcoal respectively. Studies on 56 types of fuel/stove combinations by Zhang et al. [169] showed that CO emission factor was the highest for cookstoves using coal. Still et al. [134] found that as compared to *three stone fire*, *charcoal stoves* emitted very high CO and HC (hydrocarbons) but low PM. Bhattacharya et al. [170] tested four cookstoves and reported that as compared to charcoal, wood resulted in lower emission factors for CO_2, CO and NO_x but higher emission factors for CH_4 and TNMOC (total non-methane organic compounds).

Venkataraman and Rao [164] reported much higher CO and PM emissions from dung cakes as compared to wood in traditional as well as improved Indian cookstoves. Venkataraman et al. [171] found that emissions of polycyclic aromatic hydrocarbons (PAH) using different fuel-stove combinations were much less with wood as compared to dung-cakes and briquettes. It is, thus, clearly reported that change in fuel type causes the emissions from the stove to vary. This is understandable since different types of biomass fuels can have different stoichiometric air requirement and other properties *viz*., volatile content, density, ash content, *etc*., which can affect the fuel burn rate even for the same fuel size. This affects the way bed porosity changes during combustion and hence the pressure drop through the bed. This in turn has an impact on the air supply, the extent of mixing of fuel and air and hence the combustion characteristics, resulting in variation in pollutant emissions.

5.1.2.2. Fuel size. Bussmann [31] found that *open fires* with larger fuel size took more time to reach steady state than that with smaller ones with decrease in maximum volatiles power but the efficiency was not affected. According to Dirks [166], increase in volume/surface area of fuel (hence the size of the fuel), led to decrease in power output. CO/CO_2 ratio was found to be minimum around volume/surface area ratio of 5. Bhattacharya et al. [170] reported that with increase in fuel size, there was a slight increase in CO emissions, decrease in NO_x emissions but no significant change in efficiencies of the cookstoves. L'Orange et al. [152] found negligible change in CO emissions with increase in fuel size, but there was a small decrease in PM emissions. Hasan et al. [70] report that for small fuel size, the CO/CO_2 ratio does not depend much on the fuel size. However, increase in fuel size beyond a volume to surface area ratio of about 0.5 causes a steep increase in CO/CO_2 ratio.

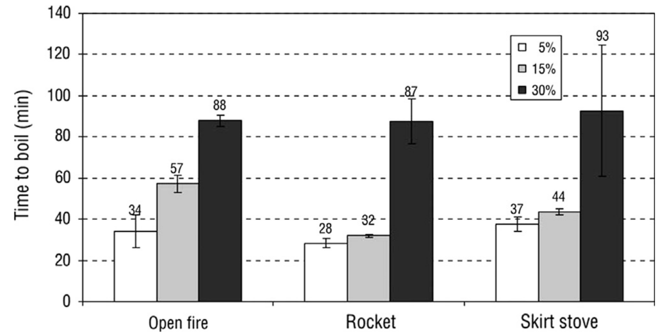

Fig. 6. Effect of moisture content on time to boil water by three cookstoves during WBT [128].
[Adapted with permission from Energy Sustain Dev 2008;12(2):66–77. Copyright 2008 Elsevier Ltd.]

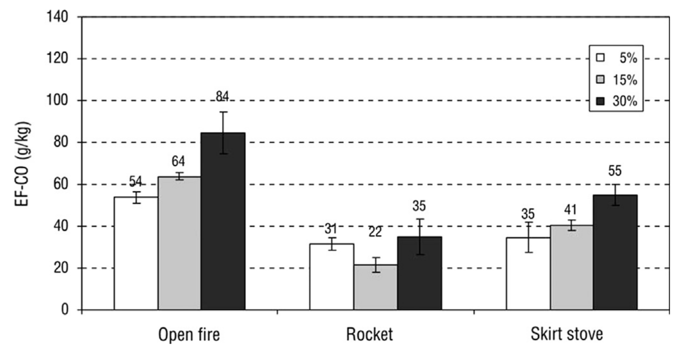

Fig. 7. Effect of moisture content on CO emissions of three cookstoves during high power phase of WBT [128].
[Adapted with permission from Energy Sustain Dev 2008;12(2):66–77. Copyright 2008 Elsevier Ltd.]

5.1.2.3. Fuel moisture content. Bussmann [31] showed that as moisture content is increased from 0% to 25%, the maximum volatile power initially decreases rapidly till about 5% moisture content and later becomes constant at design power. Claus et al. [56] while testing *Tungku Lown stove*, found that variation in moisture content from 0% to 6% using small sized fuel did not have any significant effect on efficiency and combustion performance.

Investigations by Yuntenwi et al. [128] showed that in *open fire*, *Chinese rocket stove* and *skirt stove*, with increase in moisture content from 5% to 30%, there was continuous increase in time to boil the water (Fig. 6). At higher moisture content all the cookstoves other rhan rocket stove produced higher CO emissions (Fig. 7). However, it was found that some amount of moisture is needed in wood for better combustion due to the role of OH radicals, as also pointed out by Baldwin [35]. Bhattacharya et al. [170] reported that increase in fuel moisture content decreases cookstove efficiency as well as NO_x emissions but increases CO emissions. The study by L'Orange et al. [152] showed a minimum in PM and CO emissions at about 13% moisture content. Bussmann et al. [129] found that the fuelbed behavior strongly depends on fuel moisture content only during initial phase when fire has just been lit and the fuelbed is not very hot.

5.1.2.4. Pot size and lid. Mukunda et al. [38,52] recommend pots of a large diameter to height ratio for increased heat transfer area for a given volume of the pot (Fig. 8), while Bhattacharya et al. [172] did not find any significant effect of pot size on efficiency. Experiments of L'Orange et al. [152] showed that tallest pots in their study for a given volume had a marginally better heat transfer performance. However, it was reported that the results need further validation.

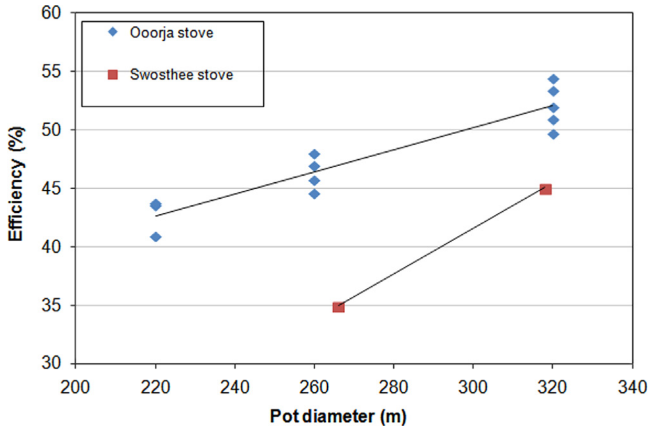

Fig. 8. Effect of pot size on efficiencies of two cookstoves (re-plotted using data from Mukunda et al. [38]).
[Adapted with permission from Curr Sci 2010;98(5):627–38. Copyright 2010 Indian Acad Sci]

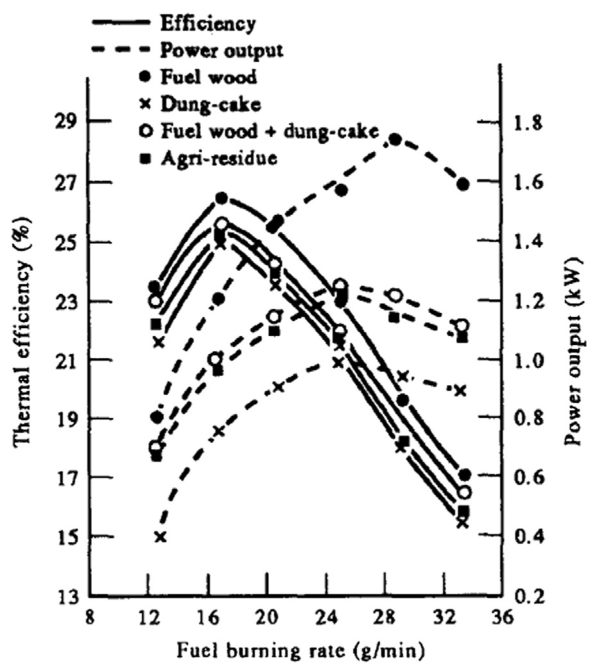

Fig. 9. Thermal performance of *Sugam II stove* [174]. .
[Adapted with permission from Renewable Energy 1994;4(5):545–9. Copyright 1994 Elsevier Ltd.]

De Lepeleire and Christiaens [42] found that at high power near boiling temperature, use of pot lid reduces evaporation losses.

It is clear that larger the pot size, the better is the heat transfer. However, it is expected that with increasing size of the pot, the improvement in efficiency would gradually saturate: this would happen since the temperature difference between the pot and the flue gases progressively decreases towards the edge of the pot. It appears that this resulted in Bhattacharya et al. [170] observing no effect of increase in pot size on the efficiency.

5.1.3. Relationship between power, efficiency and emissions

While there is near unanimity in the literature on the positive impacts of some of the design features of cookstoves, one sees conflicting reports on the relationship between efficiency and power; emissions and power; and emissions and efficiency. In this section, literature on the interplay between power, efficiency and emissions

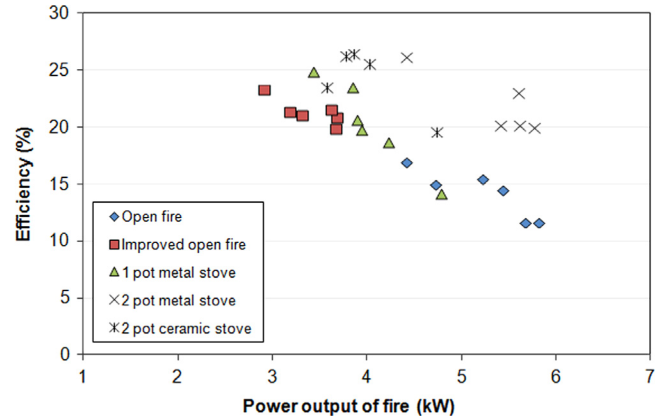

Fig. 10. Plot of efficiency *versus* fire power for different stoves (re-plotted using data from Ballard-Tremeer and Jawurek [54]).
[Adapted with permission from Biomass Bioenergy 1996;11(5):419–30. Copyright 1996 Elsevier Ltd.]

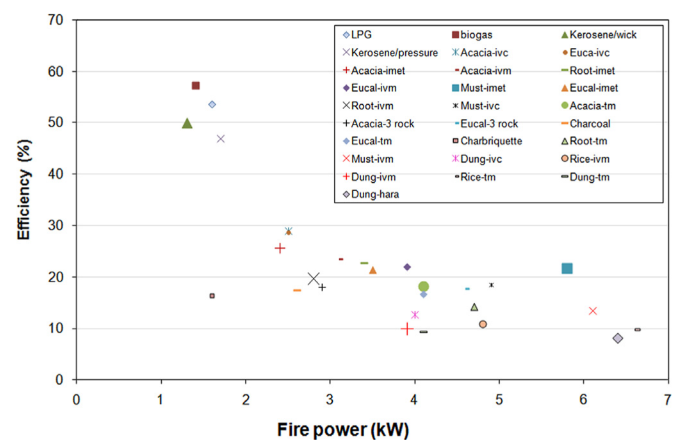

Fig. 11. Plot of efficiency *versus* fire power for different cookstove fuel combinations (re-plotted using data from Smith et al. [132]). *[Adapted with permission from Smith KR, University of California, Berkeley]* (*Note*: *ivc*: improved vented ceramic, *imet*: improved metal, *ivm*: improved vented mud, *tm*: traditional mud)

has been discussed. In order to help get a broader perspective, the present authors have compiled the data from various articles to create plots of power *versus* efficiency; power *versus* emissions and emissions *versus* efficiency. These are also presented below.

5.1.3.1. Efficiency versus power. Many cookstoves are found to have efficiency *versus* power characteristics in the shape of a shallow inverted bowl as seen in the studies of Sangen [173]. A similar characteristic is seen in the LPG burners as well [32]. For *Sugam II*, a heavy cookstove, a peak in efficiency is observed at a certain fire power, with considerable decrease in efficiency at other power values (Fig. 9) [174]. On the other hand, Ballard-Tremeer and Jawurek [54] report reduction in efficiencies with increase in fire power for five cookstoves tested by them including *open fire*, *metal* and *heavy cookstoves* (Fig. 10). While the trends are clear, there is a lot of scatter in the data. Smith et al. [132] reported efficiency *versus* power characteristics for 28 cookstove/fuel combinations including LPG, *kerosene*, *biogas* and *biomass cookstoves*. It was found that the cookstoves operating at low power and using gaseous or liquid fuels were more efficient than biomass cookstoves which were operated at higher fire power values (Fig. 11). Still et al. [134] conducted extensive laboratory studies on 18 cookstoves including *wood burning stoves with and without chimney*, *stoves with fans*, *charcoal stoves*, *liquid fuel stoves* and a

solar cooker, ranking them according to various criteria *viz.* time to boil, fuel and energy to cook, CO and PM emissions, safety provisions, initial cost and monthly fuel requirement. In this study also, the stoves with higher fire power exhibited lower thermal efficiency as compared to the stoves operating at fire powers less than around 4 kW.

5.1.3.1.1. Observations from compiled data. In order to get a broader perspective and insight from the collective data, the present authors compiled data of efficiency *versus* power available in the literature for metal stoves and mud stoves. A plot of these data can be seen in Fig. 12 (metal stoves) and 13 (mud stoves). Although there is significant scatter in the plot, there appears to be a trend of declining efficiency with increase in power, similar to that reported by Smith et al. [132]. Since all the data in these figures are for domestic cookstoves designed for a specific range of output power, it can be expected that stoves with low efficiency needed to be operated at higher fire power and vice versa: this is the observed trend in both Figs. 12 and 13. Also, it can be observed by comparing Figs. 12 and 13 that the metal stoves have higher efficiency than mud stoves in most cases. For some cookstoves like *Swosthee*, *Tamilnadu* in the metal cookstove category and *CTARA*, *ASTRA Ole* and *Improved Nouna* in the mud cookstove category, the data plotted include multiple versions of the cookstove, each with some improvement over the other: this is why these stoves seem to show multiple efficiency values at the same power.

Since the fire power for different stoves shows a wide range, it is difficult to compare trends for the different stoves from Figs. 12 and 13. In order to facilitate this, Figs. 14 and 15 are plotted by normalizing the fire power used in Figs. 12 and 13 as a fraction of the maximum fire power of each stove. The cookstoves with data corresponding to multiple versions *viz.*, *Swosthee, Tamilnadu, CTARA, ASTRA Ole* and *Improved Nouna*, have been excluded from these plots. The trends seen in these figures indicate inverted bowl shaped curves for most stoves, although there is substantial scatter. All curves show a reasonably flat behavior at most powers, except near the minimum and maximum ends. These plots also throw light on the turn down ratios of different cookstoves indicating that no cookstove gives a normalized power of less than 0.2 or a turndown ratio higher than 5. It is also significant that turn down ratio for both metal and heavy cookstoves is generally in the same range of 4–5 with a few designs having lower values.

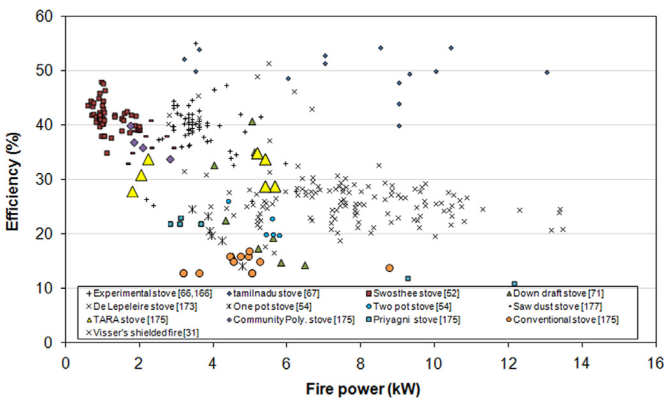

Fig. 12. Variation in efficiency with fire power for metal cookstoves (compiled by the present authors).

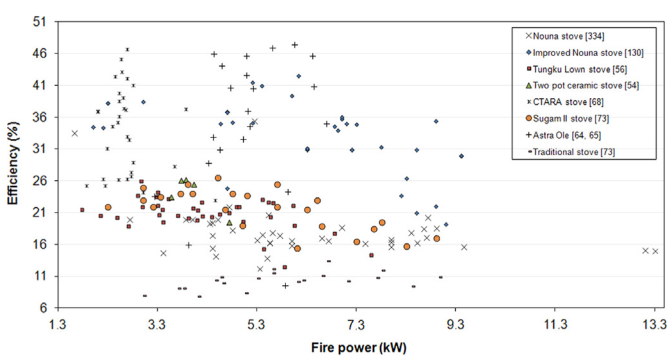

Fig. 13. Variation in efficiency with fire power for mud/ceramic cookstoves (compiled by the present authors) [334].

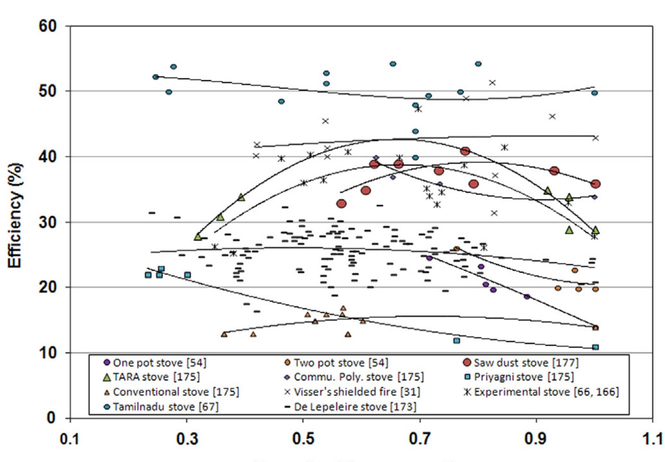

Fig. 14. Plot of efficiency *versus* normalized fire power ratio for metal cookstoves (compiled by the present authors).

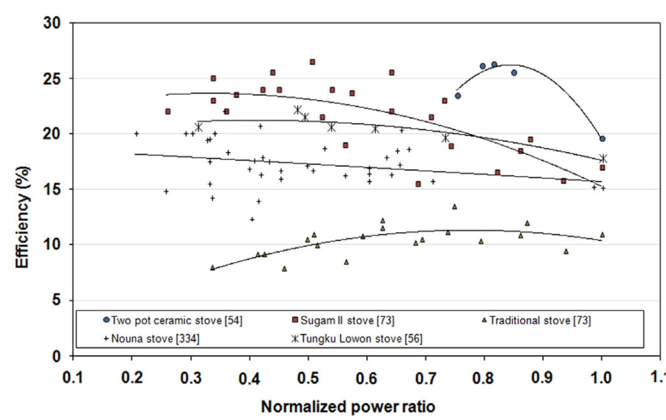

Fig. 15. Plot of efficiency *versus* normalized fire power ratio for mud/ceramic cookstoves (compiled by the present authors).

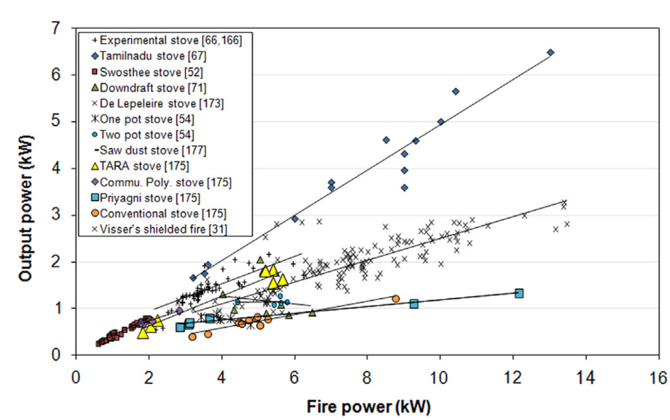

Fig. 16. Variation in output power with fire power for metal cookstoves (compiled by the present authors).

In order to verify that all these stoves give output power in a specified range, Figs. 12 and 13 are replotted to show fire power *versus* output power in Figs. 16 and 17. These figures indeed corroborate this fact that output powers of almost all the stoves in both categories is less than 3 kW, with most metal stoves giving output powers under 3 kW and most mud stoves under 1.5 kW. Trend lines of these data for individual stoves show straight lines in most cases, confirming that the stoves show a reasonably flat efficiency *versus* fire power as seen in Figs. 14 and 15. It is however worth noting here that the slope of these straight lines is not numerically equal to their efficiency owing to non-zero intercepts.

5.1.3.2. Emissions versus power. Even on relationship between emissions of different pollutants and power, there is no unanimity in the literature. Claus and Salilatu [53] have plotted this variation for three cookstoves made of different materials. A much steeper increase in CO emissions was observed with increase in power for heavy metal cookstove and mud cookstove as compared to brick stove. Kandpal et al. [174] also report increase in CO emissions with power for the cookstove *Sugam II* using different fuels (Fig. 18). Many other researchers also report increased CO/CO_2 ratio or CO emissions at increased power [53,56,67,73,130]. However, in one set of studies

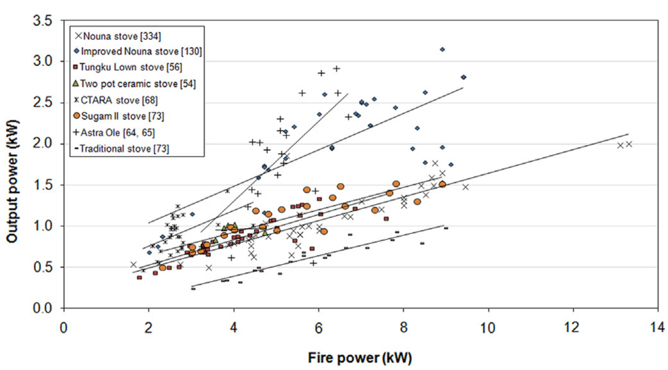

Fig. 17. Variation in output power with fire power for mud/ceramic cookstoves (compiled by the present authors) [334].

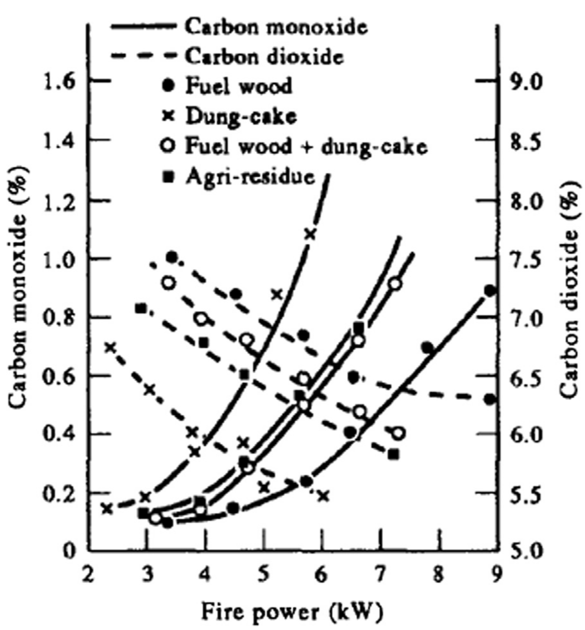

Fig. 18. Variations in CO and CO_2 emissions with fire power for *Sugam II stove* [174]. [Adapted with permission from Renew Energy 1994;4(5):545–9. Copyright 1994 Elsevier Ltd.]

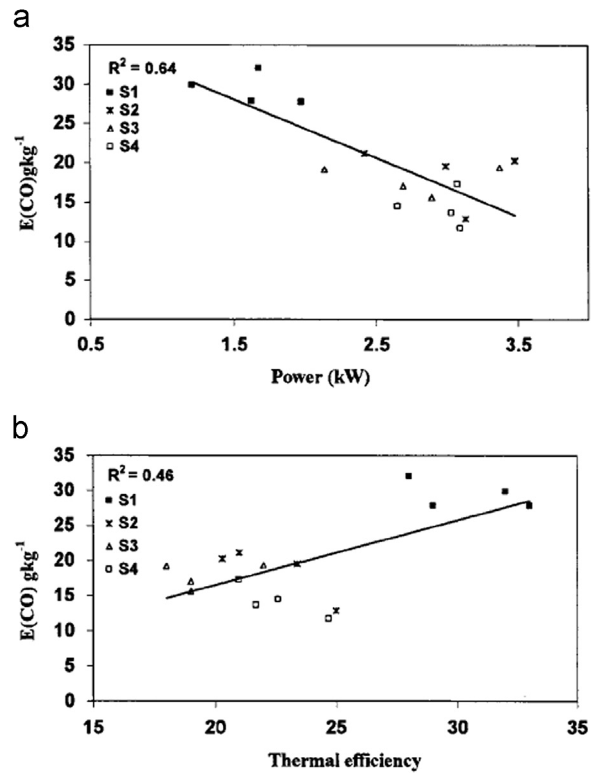

Fig. 19. Variation in CO emissions with (a) fire power and (b) thermal efficiency for four cookstoves [164]. (*Note*: *S1*-metal stove, *S2*-Grihalaxmi stove, *S3*-traditional stove, *S4*-Bhagyalaxmi stove).
[Adapted with permission from Environ Sci Technol 2001;35(10):2100–7. Copyright 2001 American Chemical Society]

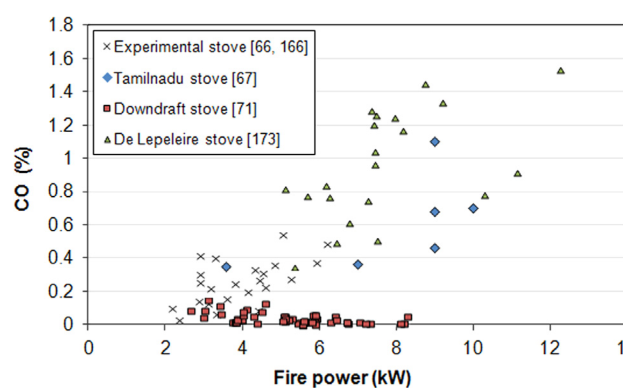

Fig. 20. Variation in CO (%) with fire power for metal cookstoves (compiled by the present authors).

[131,135,164,175] using different cookstove–fuel combinations, opposite trends were observed. Venkataraman and Rao [164] found CO emission factors in four cookstoves using dung cake reducing with increase in power (Fig. 19a). Agenbroad et al. [111,113] using carbon balance approach found that in *rocket elbow stove*, PM first decreased with increase in non-dimensionalised power with very low values of PM over a wide range of the non-dimensional power, beyond which the PM increased further, giving a bowl like shape for PM *versus* power plot.

5.1.3.2.1. Observations from compiled data. Here again, in order to look for the insight provided by available data collectively, the present authors have compiled the available data on emissions of metal and mud cookstoves as a function of fire power (Figs. 20–22).

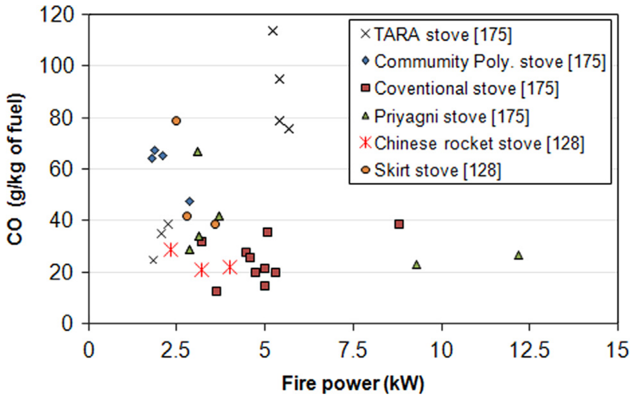

Fig. 21. Variation in CO (g/kg of fuel) with fire power for metal cookstoves (compiled by the present authors).

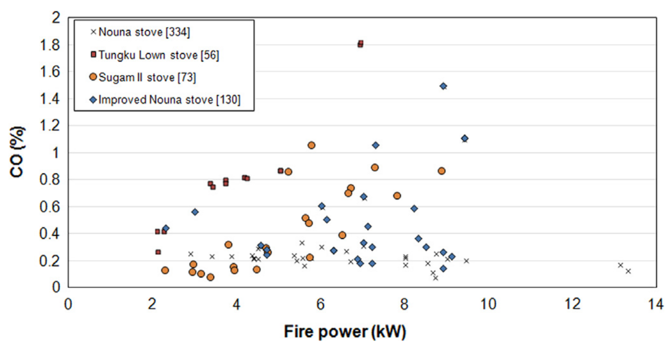

Fig. 22. Variation in CO (%) with fire power for mud/ceramic cookstoves (compiled by the present authors) [334].

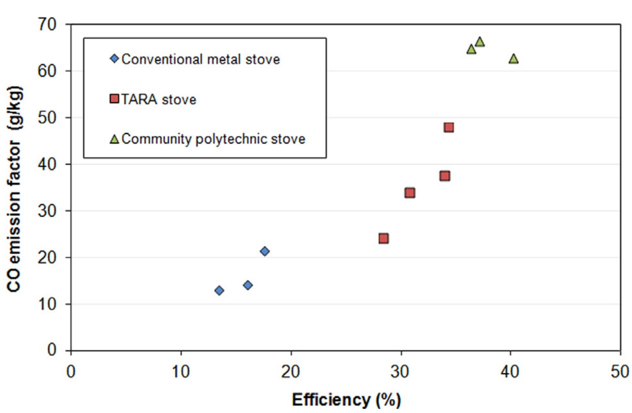

Fig. 23. Variations in CO emission factor with efficiency for metal stoves (re-plotted using data from Ahuja et al. [135]).
[Adapted with permission from Biomass 1987;12(4):247–70. Copyright 1987 Elsevier Ltd.]

It can be seen from Fig. 20 that the cookstove operating on downdraft principle [70,71] has lowest CO emissions (as percentage in exhaust gases). For all other cookstoves in that figure, there is a clear trend of increasing emissions with increasing power. Compilation of data available in the form of CO emission factors (as g of CO per kg of fuel used) for metal cookstoves (Fig. 21) has a very high scatter and does not show a clear trend. Some of these cookstoves show clusters of CO emissions in narrow power range due to the use of different fuels. Data on CO emissions from mud/ceramic cookstoves as percentage of exhaust gases in Fig. 22 shows very small variations in CO emissions over a wide power range for *Nouna stove* and increase in CO emissions with power for different fuels in *Sugam II* and *Tungku Lown*. In case of *improved*

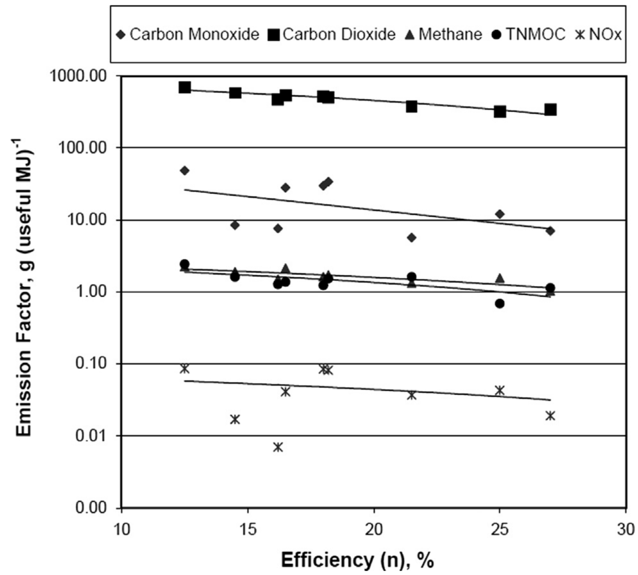

Fig. 24. Variation in emission factors of different pollutants with thermal efficiency for wood-fired cookstoves [172].
[Adapted with permission from Biomass Bioenergy 2002;23(6):453–69. Copyright 2002 Elsevier Ltd.]

Nouna stove there is a lot of scatter, since the data corresponds to different versions of the stove incorporating improvements in the cookstove design. Comparing these figures, it emerges that one cannot conclude whether metal stoves are better or mud stoves from CO emissions point of view.

5.1.3.3. Emissions versus efficiency. Venkataraman et al. [164] found a positive correlation between CO emissions and efficiency (Fig. 19b). Ahuja et al. [135] also found increase in CO emissions with efficiency for different cookstoves (Fig. 23). On the other hand, tests on 24 types of *traditional* and improved cookstoves using wood and charcoal by Bhattacharya et al. [170,172] showed decrease in emission factors of various pollutants with increase in efficiency (Fig. 24). Kandpal et al. [176] also report that the traditional *U shaped mud stove* emitted 2–3 times more CO, 1.5–1.65 times more N_2O and 1.5–1.6 times more HCHO (formaldehyde) as compared to improved mud stove *Sugam II*.

The work of Ballard-Tremeer and Jawurek [54] shows that for three closed cookstoves, there is an increase in efficiency with increase in emissions for a part of the curve, while efficiency decreases with further increase in emissions (Fig. 25). For open fire, the measurements show only a positive correlation between the two and no trend was visible for open fire with grate. They also found that emission performance of open fire with grate was the best in the lot studied. The study of Still et al. [134] on 14 solid biomass stoves showed no clear trend between thermal performance and emissions across stoves.

5.1.3.3.1. Observations from compiled data. The plot of CO emission factors (g/kg of fuel) as a function of efficiency of metal stoves compiled from the literature by the present authors (Fig. 26) shows no clear correlation for individual cookstoves with each cookstove having its own cluster with considerable scatter, at times due to operation using different fuels. However, across cookstoves, there is clearly a positive correlation between CO emission factors and efficiency.

5.1.3.4. Correlations between pollutants. Venkataraman and Rao [164] found that for various cookstove–fuel combinations, there

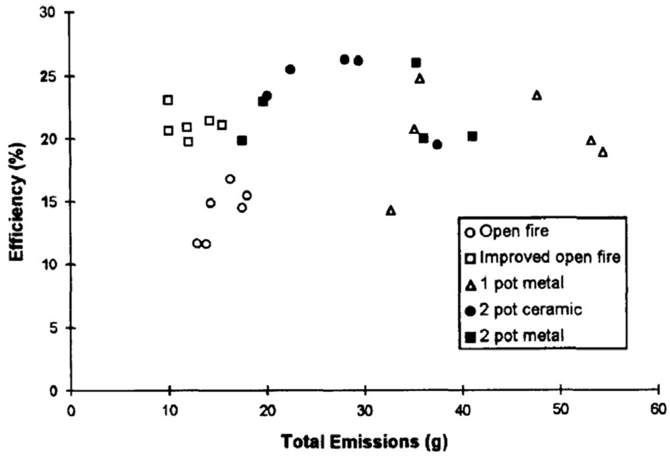

Fig. 25. Plot of efficiency *versus* total emissions for different cookstoves [54]. [Adapted with permission from Biomass Bioenergy 1996;11(5):419–30. Copyright 1996 Elsevier Ltd.]

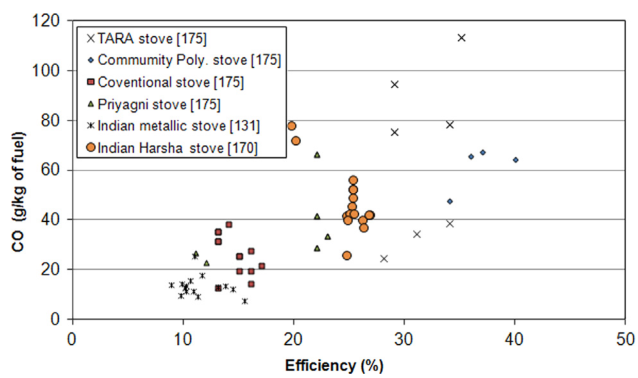

Fig. 26. Variation in CO (g/kg of fuel) with efficiency for metal cookstoves (compiled by the present authors).

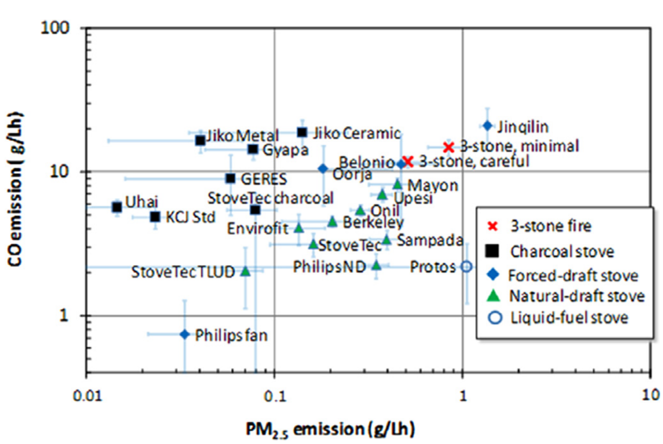

Fig. 27. CO *versus* $PM_{2.5}$ emissions during low power simmering phase of WBT [90]. [Adapted with permission from Environ Sci Technol 2012;46:10827–34. Copyright 2012 American Chemical Society].

was a good positive correlation between CO and PM emission factors. According to McCracken and Smith [163] as well, there is a strong positive correlation between average kitchen concentrations of CO and TSPs and hence CO concentrations can be used to estimate $PM_{2.5}$ concentrations. Jetter et al. [163] also found the same during low power simmering phase of WBT irrespective of the type of the cookstoves (Fig. 27). In contrast for a powdery biomass cookstove, Venkataraman et al. [177] found increase in PM emissions and decrease in CO emissions with increase in both vertical port radius and combustion temperature. Hence the authors suggested that for the small natural draft combustion systems such as cookstoves, the estimate of PM emissions should be done independently and not from CO emissions. This negative correlation between CO and PM appears to be due to the distinctly different design of a powdery biomass cookstove, with the powdery form of the fuel specifically contributing to the PM emissions. Roden et al. [178] did not find a correlation between CO and PM emissions and have specifically advised against estimating PM from CO measurements.

5.1.3.5. Explanation for the conflicting trends in literature. The above results show conflicting reports in the literature on the relationship between power, efficiency and emissions. To analyze this, the processes taking place in a cookstove need to be looked at in-depth. A qualitative analysis reveals that for any cookstove, at very low power, the heat released is expected to barely provide for the losses due to sensible heating of the cookstove body and to the environment, resulting in very small efficiency at such power levels. With increase in heat release rate, the useful gain by the pot contents should go up while the losses due to sensible heating of the cookstove body will not go up proportionately leading to increased efficiency. Further increase in power will have a higher heat transfer coefficient on the fire side of the pot base and if the pot used for the test has a large enough diameter, it will be able to pick up more heat so as to have a nearly constant efficiency with increase in power. However, if the pot diameter becomes a limiting factor in the heat transfer to the pot, flue gas losses will increase with increased heat release rate and hence the efficiency will go down with increase in power.

Thus, theoretically, all stoves are expected to have efficiency *versus* fire power characteristic curve in the form of an inverted bowl, meaning thereby that efficiency is expected to be maximum in a certain range of fire power. This is evident in some of the plots given in the literature [102,104,173]. This trend also emerges clearly from plots of efficiency with normalized power compiled as part of the present work in Figs. 14 and 15. Where the peak occurs and how flat the bowl is depends on the thermal mass of the stove and the size of the pot.

In view of the above, the conflicting trends in efficiency *versus* power can be explained as follows:

(a) In many tests reported in the literature, the entire range of fire power would not have been covered. In particular, the lower end of power range is usually not captured in most papers in the literature, resulting in conflicting reports.
(b) High levels of uncertainty compounds to this problem, smearing out any observable trends.
(c) Contrary to the recommendations of Krishna Prasad et al. [34] and Bhatt [127] that efficiency needs to be obtained at various values of fire power and always reported with the power at which it was obtained, even modern stove test protocols include only at most two power levels at which to obtain and report efficiency.
(d) Moreover, many papers report efficiency within narrow range of power levels but with variations in other parameters such as fuel or pot size, and some papers have no mention of power levels of the test, making interpretations of the data even more difficult.

The conflicting reports of the CO *versus* power and CO *versus* efficiency trends also need to be analyzed. As argued by Ahuja et al. [135] and Joshi et al. [175], as power increases, combustion chamber temperatures increase, which has a tendency to promote complete combustion leading to decrease in CO emissions. In contrast, according to Kohli [108] and Priestley [179], in natural draught stoves, as the temperature increases, the induced airflow rate shows

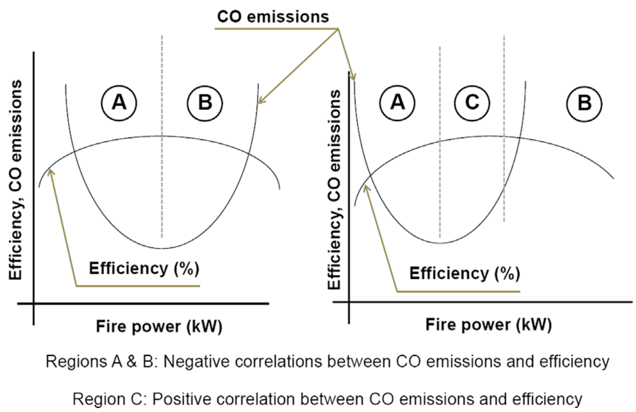

Fig. 28. Hypothetical curves showing variations in thermal efficiency and CO emissions with fire power.

a maximum, beyond which airflow rate declines. This could result in an increase in CO even when the fire power increases. The latter argument is clearly supported by observations in the literature: negative correlation between CO emission and power is observed in lower power ranges. At higher powers, generally there is an increase of CO with power. A minimum in CO emissions with power is also reported by Hasan and Khan [71]. Thus the CO emission *versus* power characteristics over a wide range of power are expected to have the shape of a bowl: emissions first decreasing with increase in power and for higher power ranges, increasing with increase in power.

For a given cookstove operated with a given pot size, CO emissions may show a minimum at a certain value or range of fire power, while overall efficiency may show a maximum at some other range of fire power. The fire power ranges for minimum CO and maximum efficiency need not be the same. In the case where the peak efficiency occurs in the same power range as minimum CO, the trend of efficiency verses CO would be negative at all power levels; whereas in the more general case where these power ranges corresponding to minimum CO and maximum efficiency are different, there would exist a certain range of power levels where the correlation between efficiency and CO is positive, while elsewhere it will be negative (Fig. 28). In literature both positive and negative correlations between efficiency and CO emissions can be observed (Fig. 25).

A word about uncertainties of measurements is also in order. Even in the 1980s, some authors pointed out the importance of statistical analysis of the data collected. Baldwin [35] presented detailed guidelines for statistical analysis in stove testing. However, a large body of data available in the literature is without the backing of statistical analysis, which also adds to the difficulty in drawing concrete conclusions regarding the trends observed.

5.2. Cookstove performance in the field

The challenges of determining field level performance of a cookstove are quite different from the laboratory level testing, since one of the primary requirements of such a study is the willingness of the household to allow outsiders to make measurements and the former's close co-operation in the same. Even the instruments have to be sturdy and operable on battery in case there is no electricity supply in the place of test. Grappling with field level difficulties of varying ambient conditions as well as operating conditions is also a challenge particularly in interpreting the results of the test.

The earlier field studies have focused on thermal performance in terms of fuel savings. The study by Gupta et al. [153] showed that 77% of the households surveyed gave satisfactory report about saving in fuel as well as time for cooking due to use of an improved cookstove as compared to the traditional cookstove. Adkins et al. [180] carried out a similar study in the field using CCT 2.0 and found that an improved cookstoves, *StoveTec* was preferred by a majority of the households due to its faster cooking time, convenient size, removable pot skirt and other design features.

It is encouraging to note that most of the field studies in different parts of the world have found substantial reduction in CO as well as PM emissions with the use of improved cookstoves as compared to the traditional ones [153,156,181–191]. Smith et al. [191,192] reported that use of improved cookstove reduced kitchen levels of CO and particulates by 30–70% and 25–65% respectively and also reduced fuel consumption. As a cookstove becomes old, it may result in higher emissions as was found by Wei et al. [193]. They observed that a 15 year old improved cookstove emitted 2.5 times more PM as compared to the one year old cookstove of the same design. Roden et al. [155] conducted field tests for estimation of real-time emissions during combustion in *traditional Honduran cookstove.* Both PM and CO emission factors were very high. The emissions of PM, elemental carbon (EC) and total carbon (TC) had no correlation with fuel moisture content.

At times, replacement of traditional cookstoves with improved ones resulted in reduction in fuel consumption but not in the CO and PM emissions [194]. Some studies also showed that even with improved cookstoves, the exposure of users and other family members to emissions was much higher than the acceptable limits as per WHO/national standards [186,195–199]. It was also reported that overall indoor levels of pollutants were the lowest in houses using LPG and increase in the order of using kerosene, coal, wood and cattle dung. NO_2 was the only pollutant with high levels in LPG-using houses [20,200–202]. In one study of more than 400 households, the personal exposure to the respirable particulate matter (RPM) *i.e.* PM_{10} was found to be about 70 μg/m^3 for households using LPG/kerosene whereas it was about 2000 μg/m^3 for those using biomass as fuel [20]. From a study of 400 households in some regions of rural India, Balakrishnan et al. [203] reported that 24-h average kitchen concentrations of respirable particulates (μg/m^3) for households using gas, kerosene, wood and dung as cooking fuels were 61, 156, 340 and 470 μg/m^3 respectively. For dung, the value is almost 10 times the limit given for PM_{10} in WHO guidelines for Air Quality [138].

A few researchers have focused on correlating the PM and the CO emissions at the field level. Using linear regression, Northcross et al. [204] found that for both traditional as well as improved stoves CO emissions can be used to estimate PM emissions as well. Naeher et al. [205] found the same to applicable for *open fires* or *plancha stove* but not for *gas stove*. On the contrary, field studies by Li et al. [206] showed decrease in $PM_{2.5}$ emission factor with an increase in CO emission factors. They also observed an increase in $PM_{2.5}$ emission factor at higher cookstove efficiencies.

5.2.1. Laboratory versus field performance

Discrepancy between the emission performance of a cookstove in the laboratory and in the field has also been highlighted by some researchers. The comparison of laboratory level WBTs and field level KPTs by Bailis et al. [207] showed that there can be discrepancy between the lab and field results of thermal performance of cookstoves. Only the low power simmering results in the lab had a correspondence with KPT results in the field. Thus, it is emphasized by them that lab level conclusions should not be extended to the field without carrying out KPTs in the field.

Roden et al. [178] noted that the emission factors of CO as well as PM for many cookstoves were significantly larger in field experiments than those measured in laboratory studies of the

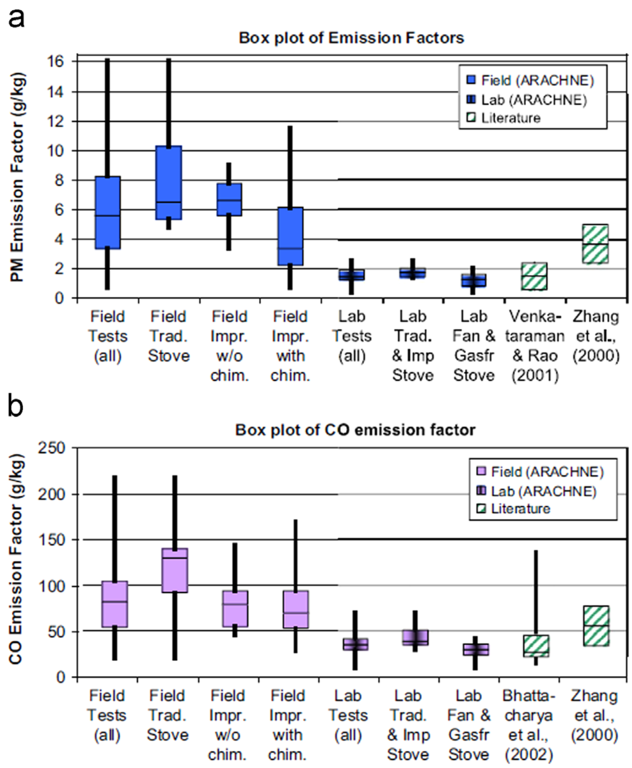

Fig. 29. Variation in emission factors of PM and CO during field and lab studies [178].
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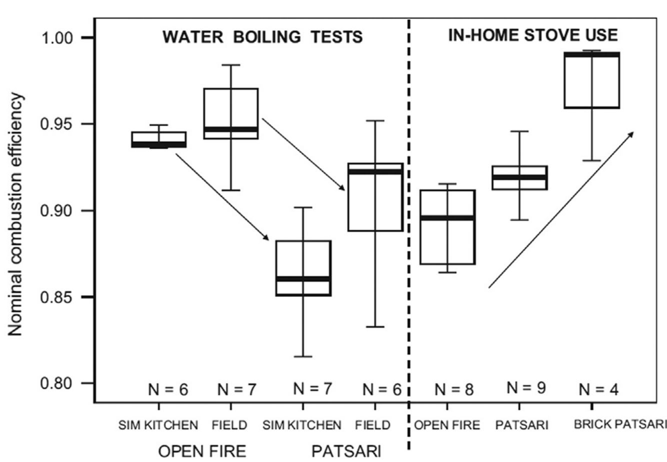

Fig. 30. Nominal combustion efficiencies for different stove/test type [182].
[Adapted with permission from Atmos Environ 2008;42(6):1206–22. Copyright 2008 Elsevier Ltd.]

same cookstoves (Fig. 29). It was therefore suggested that the use of the emission results obtained from the lab tests should be limited to the comparison with other cookstoves and not for estimation of real-world emissions. They also suggested that CO emissions should not be used for estimation of PM emissions in the field. Johnson et al. [182] found that emission performance of *Patsari stoves* was better than that of open fires during field tests. These trends were opposite to the results observed by the authors during laboratory level WBT tests (Fig. 30). Li et al. [206] observed that with an increase in CO emission factor, there was decrease in $PM_{2.5}$ emission factor, an observation opposite to that seen in many of the laboratory studies (Fig. 27).

Though biomass is grown renewably, its inefficient combustion produces green house gases which increase global warming potential of biomass fuels [208]. Some researchers have used field level measurements of emissions and estimated that the emissions from biomass cookstoves can contribute substantially to global warming. [19,208–216].

5.3. *Conclusions from cookstove testing literature*

The reports on laboratory and field measurements on a wide variety of cookstoves have resulted in wide variety of information: some of the reports are in agreement with each other while some others are at variance. The discussions above have attempted to give an explanation to conflicting reports in the literature. The following conclusions can be drawn from the literature presented above and the accompanying discussion:

(a) The gasifier stoves are cleaner burning and have higher efficiency than combustion stoves as seen in the laboratory as well as the field.
(b) In combustion stoves, features like use of light weight material, grate, insulation, preheating and swirl of air, forced draught, smaller fuel size, optimal spacing between pot and the shield, *etc*. have a positive impact on the performance of the cookstove.
(c) In general, change in fuel type causes the emissions from a cookstove to vary.
(d) It is fairly established from the literature that an optimum value of moisture is required in the fuel for clean combustion. However, the value of that optimal is given as 13% only by one group of researchers. This needs further investigation.
(e) It is also clear that larger the pot size and heat transfer area, the better is the heat transfer, and this shows a saturating trend with further increase in heat transfer area.
(f) Even the laboratory measurements on cookstoves show a lot of scatter in data indicating very high uncertainty which can, at times, smear out the trends in the data.
(g) There are conflicting reports on relationship between efficiency of a cookstove and the fire power: some indicating near invariance of efficiency with increase in power, some giving decrease of efficiency with increase in power, some giving opposite trends, some showing a range of power with maximum efficiency and a few others giving no trend at all. An in-depth understanding of the processes in a cookstove supports the characteristic of efficiency *versus* power having an inverted bowl shape over a wide range of fire powers. Thus, depending upon the range of power over which the cookstove is tested, one may get any of the trends indicated above. If the data has very high uncertainty, no clear trends will emerge from the data.
(h) Similarly the CO emissions *versus* power is expected to show a minimum over a wide range of fire power. If the measurements do not cover the entire range of power, the observed trends may show a positive or negative correlation between the efficiency and fire power.
(i) As a consequence of the points (g) and (h) above, the CO *versus* efficiency curve is expected to show either a positive or a negative correlation depending upon the actual shape and relative positions of the efficiency *versus* power and CO *versus* power characteristics for the stove.
(j) The correlations between CO and PM appear to be strongly dependent on the cookstove design and the fuel. There is no agreement on the correlations between the two pollutants either at the laboratory or at the field level. Thus, it appears to be better to have separate measurements for the two.

(k) A discrepancy between laboratory and field tests reported by many has led researchers to suggest that laboratory data should not be used for projecting gains in the field.

6. Health issues related to use of biomass cookstoves

Exposure to pollutants from biomass cookstoves can result in acute respiratory infection in children, adverse pregnancy outcomes in women, and chronic lung diseases [19]. Some of the emissions from the stoves, *viz*., CO_2, CH_4, N_2O and aerosol particles in atmosphere can also add to the greenhouse effect and hence contribute to climate change [217].

Since the 1980s, the health problems of poor women and children in developing countries due to exposure to the dangerous emissions from traditional cookstoves have been recognized [195]. It is estimated that in developing countries, one person dies every 20 s due to various diseases caused by indoor pollution [218]. Each year about 1.4 million people die due to inhalation of smoke from traditional cookstoves [219]. In developing countries, victims of indoor air pollution are mostly women and children [220,221].

From 1980 to 2010 the percentage of households relying on solid fuels worldwide has decreased from 62% to 41% but during this period the actual number of people exposed to indoor pollution due to solid fuel use has been almost stable at about 2.8 billion [222]. Several studies relate the health impacts of biomass cookstoves to global/regional burden of diseases [222–229].

Many researchers have carried out reviews of studies on health effects of biomass cookstoves [224,225,228,230–242]. The number of studies in the field with systematic measurements on traditional or improved woodstoves and corresponding fuel savings and impact on health is rather limited. There are far more studies on health issues linked with emissions from cookstoves. Naeher et al. [241], in their extensive review of studies on health effects caused due to wood combustion, conclude that there is insufficient evidence to say that particulates emitted from wood combustion are less or more health damaging than fine particles in the general ambient air. However, it is acknowledged even by them that providing cleaner burning cookstoves is a major step forward in addressing the health problems related to emissions. Kim et al. [242] conducted an extensive review of various diseases associated with household use of biomass fuels. The authors categorized the diseases associated with exposure to biomass smoke into two types *viz*. respiratory and non-respiratory diseases. The respiratory diseases include pneumonia, acute lower respiratory tract infection (ALRI), chronic obstructive pulmonary disease (COPD), tuberculosis, lung cancer and asthma. The non-respiratory diseases include still birth, low birth weight (LBW), infant mortality, cardiovascular disease, cataract, nasopharyngeal & laryngeal cancer, headache *etc*. About 4–5% of population of developing countries is at risk of various respiratory and non-respiratory diseases due to use of solid fuels [228]. Table 4 summarizes the diseases associated with use of biomass cookstoves and studies conducted by various researchers.

Table 4
Health issues related to stoves.

Type of disease				Studies related to disease
(A)	Respiratory disease			[228,247,262–265]
	(i)	(a)	Pneumonia	[239,243,266]
		(b)	ALRI	[231,240,244,245,251,252,267–269]
	(ii)	COPD		[228,240,251,252,258,270–278]
	(iii)	Tuberculosis		[250,251,256,279–281]
	(iv)	Lung cancer		[233,251,282–290]
	(v)	Asthma		[248,291–294]
(B)	Non-respiratory disease			
	(i)	(a)	Still birth	[253]
		(b)	Low birth weight	[254,255,295,296]
		(c)	Infant mortality	[223,254,297,298]
	(ii)	Cardiovascular disease		[252,299,300–304]
	(iii)	Cataract		[251,257,305–307]
	(iv)	Others		[258–260,308–310]

6.1. Some studies on respiratory diseases

Smith et al. [243] conducted a study to estimate the effect of chimney stoves on reduction of the risk of pneumonia in Guatemalan households originally using open fires. The authors suggested for reduction in exposure to biomass smoke, use of clean fuels and cookstoves with cleaner combustion. Dherani et al. [239] conducted a review of risk of pneumonia in children under 5 years of age, exposed to combustion products of solid fuels. It was estimated that the risk of pneumonia in the children exposed to solid fuel combustion increases by a factor of 1.8. Bates [244] conducted a case study in Nepal on 917 children and found that use of biomass as well as kerosene as cooking fuels may cause high risk factors for ALRI in Children. In South Asia more than 8% of the burden of disease is caused due to ALRI [220,245]. It is reported that China has higher rate of COPD than India due to more use of coal as fuel [228]. Diaz et al. [246] and found that about 1/3rd of the Guatemalan women using traditional open fires for cooking were at risk of developing COPD. Riojas-Rodríguez et al. [247] report that in rural Mexico Higher firewood use was associated with common cold and breathing issues in women It was found that fuel efficient stoves were associated with lowering risk of common cold. and complicated respiratory diseases. Sinton et al. [248] reported that use of coal for household cooking and space heating was associated with childhood asthma and adult respiratory diseases in China. Lakshmi et al. [249] conducted a case study in north India and found that the use of biomass fuel increased the risk of tuberculosis. Mishra et al. [250] concluded the same from the analysis of the data from National Family Health Survey. According to Smith and Liu [233], exposure to smoke due to combustion of solid fuels for cooking increases the risk of lung cancer. Baumgartner et al. [251] report that household air pollution is directly associated with COPD, ALRI, lung cancer, and tuberculosis.

Wilkinson et al. [252] conducted two case studies, one in India and the other in UK for estimation of indoor emissions and found that Indian improved cookstove program was beneficial for reduction in various diseases associated with biomass use.

6.2. Some studies on non-respiratory diseases

Lakshmi et al. [253] used data from a district level household survey and estimated that use of clean fuels for cooking can reduce about 12% of stillbirths in India. The analysis by Epstein et al. [254] of data from India's National Family Health Survey III showed increase in risk of LBW and neonatal deaths due to the use of kerosene, biomass and coal. Thompson et al. [255] found that in rural Guatemala use of chimney stoves reduced exposure to CO in pregnant women by 39% as compared to those using open fires resulting in reduction in LBW cases. According to Balakrishnan et al. [223], about 627,000 estimated premature deaths in India are caused due to ambient $PM_{2.5}$ emissions, 25% of which are due to use of household solid fuels. Pokhrel et al. [256] conducted a case study in Nepal and found that use of solid biomass as well as kerosene fuels increase the risk of cataract in women. Mishra et al. [257] studied the effect of cooking fuel on frequency of occurrence of partial or complete blindness using data from National Family Health Survey. It was estimated that the risk of partial blindness is drastically increased due to the smoke exposure from the use of biomass fuels for cooking. Diaz et al. [258] found that in

Guatemala, use of *Plancha stove* in place of open fires drastically reduced the health problems such as sore eyes, headache and back pain in women. The study by Siddiqui et al. [258] in southern Pakistan showed that use of wood as cooking fuel was associated with symptoms of eye and respiratory problems. According to Pintos et al. [260], use of wood stoves is associated with cancers of the upper aero-digestive tract. Peabody et al. [261] found that the exposure of a person to indoor air pollution depends more on fuel type than on stove type. Reduction in exposure to indoor air pollution is possible by reducing household use of coal, using improved cookstoves in better ventilated kitchens.

7. Dissemination and adoption of biomass cookstoves

Worldwide more than 160 improved cookstove programs were reported to be running in 2011, focusing on wide dissemination of improved cookstoves [23]. Every program has its own strategies for disseminating the cookstoves. At the same time, for success of any improved cookstove program, the new cookstoves should be accepted by the people and they should be used continuously on long term basis. The literature on dissemination can focus on one or both of these aspects: (i) providing information about the dissemination strategies and methodology (ii) discussing the responses of the users to the cookstoves disseminated through these programs. The two aspects are generally closely linked. Thus, a critical appraisal of any dissemination program would include the assessment of the strategies vis-à-vis the reasons for users' acceptance/non-acceptance of the cookstoves disseminated.

7.1. Some studies on dissemination of improved cookstoves

Barnes et al. [311] reported review of improved cookstove programs worldwide which included comparison of various programs, reasons for promotion of improved stoves, role of government, donor agencies and subsidies. According to the authors, it must be possible for the improved cookstove to be locally manufactured easily, these stoves must be easy to operate, durable and must result in clean combustion. Barnes et al. [312] reported a review of development and dissemination of improved cookstoves across the world and highlighted the characteristics of successful dissemination programs. Rahman [16] reported the details of improved cookstove programs conducted in different south Asian countries. The author also discussed barriers to dissemination of improved cookstoves. During 1984–2001 more than 34 million improved cookstoves of various designs were reportedly disseminated in India under this program [15]. The achievements, however, were limited on the field due to various reasons discussed by Barnes et al. [15].

In China, National Improved Stove Program (NISP) was launched in early 1980s by Ministry of Agriculture. The main aim of the program was to provide people with improved stoves for cooking as well as space heating using biomass or coal as fuel. Till the late 1990s nearly 200 million improved stoves were disseminated in China through NISP [248,313]. NISP was successful due to strong administrative and technical support, availability of resources at local level and motivation as well as continuous attention at national level [248]. Smith et al. [314] reported details of NISP and lessons to be learned by other countries for success of cookstove programs. Smith and Keyun [313] reported the highlights of the NISP and brought out the need for a new program, NISP-II, to reduce air pollution in China in the 21st century.

Shyam Sundar [315] reported of dissemination of *Agni stove* in Sri Lanka over a period of 15 years. The author presented following steps for commercialization of a cookstove: (i) research and development according to needs of users; (ii) definition of target users and setting up the production base; (iii) stove dissemination through proper channels; (iv) wider stove dissemination and (v) evaluation of acceptance of stove and follow previous steps if required. In Sri Lanka, the potential for saving the fuel wood was estimated at about 41% but the estimated consumption of fuel wood in improved cookstoves was only about 12% of the total fuel wood consumption in 2002 [316].

In Bangladesh, improved cookstove program was started in 1978 by The Institute of Fuel Research and Development (IFRD) of the Bangladesh Council of Scientific and Industrial Research (BCSIR). About 1.8 lakhs improved cookstoves were disseminated in Bangladesh from 1994 to 2001 in two phases [317]. Alam et al. [318] reported impact of *improved earthen stoves* disseminated in Bangladesh on fuel savings and health improvement. In Nepal, during 1950s, *Hyderabad stove* and *Magan Chulha* were introduced [319]. The improved cookstove program in Nepal was started in 1980s and under which about 95,000 improved cookstoves were disseminated till 2002. Karekazi and Turyareeba [17] reported a review of improved cookstove programs in several eastern African countries. Close to one million improved cookstoves were disseminated in these countries till 1993. Various improved cookstoves used in this region include *Maendeleo stove*, *Y stove*, *Kilakala stove*, *Kenyan Ceramic Jiko*, *improved soapstone stove* and *community* (*institutional*) *stove*.

Hanbar and Karve [320] gave a detailed account of various features of the cookstoves program NPIC in India and the benefits that accrued from the program. Kishore and Ramana [321] reported that in India, the actual benefits of the NPIC were very low, as compared to the same mentioned in the government reports. According to the authors, development and dissemination of long life (5–7 years) improved cookstoves can enhance the impact of such a program.

Barnes et al. [15] have discussed the implications of Improved Chulha Programmes in India and worldwide. The findings of a survey conducted in selected districts of six states in India, where the program had yielded best results, were presented. Apart from identifying the best practices followed in these places, the problems faced were also highlighted. One of the practices commonly encountered by the authors was the modification in the dimensions of stove body and chimney by the users in accordance with their convenience. A need for greater interaction between the stove designers and the users was highlighted by the authors. The authors also discussed about India's new initiative for development and dissemination of advanced biomass cookstoves [25].

In Karnataka, India, an improved two pan mud stove *sarala ole*, a simplified version of *ASTRA ole*, was disseminated by two NGOs with the help of women, who designed their own improved cookstoves as per their requirements [322]. The TERI designs disseminated at residential tribal schools at Doimukh in Arunachal Pradesh and Kankia in Orissa have been reported to produce more than 50% fuel-wood saving [75]. A *HELPS rocket chimney stove* was successfully adopted in Guatemala due to its high combustion efficiency and operation with less smoke [323].

Shrimali et al. [324] reported six elements of commercial cookstove business models *viz.* technology and design choices, target customers, financial models, marketing strategy, channel strategy and organizational characteristics. A social network of men, women and government officials can help in transferring information on improved cookstoves [325].

7.2. Some studies on adoption of improved cookstoves

Adoption of particular improved cookstove depends on mainly three factors *viz.* (i) *social,* which include family size and meal occasion, (ii) *functional,* which include ability of improved cookstove to provide space heat and ambient light, (iii) *cultural,*which include local norms and traditional foods [326]. According to one study, the willingness of people for adoption of improved

cookstove mainly depends on their education and household income [327].The barriers to adoption of improved cookstoves include 'social, economic, political, cultural and institutional factors which can be overcome by active role of government and non-governmental organizations [327]. Ruiz-Mercado et al. [328] used real-time measurement of cookstove body temperature over a period of 32 months for monitoring the extent of usage of the improved chimney stove. Edwards et al. [329] reported the importance of sample size (number of households for field study) for conducting field studies and evaluating actual benefits caused due to improved cookstove use. The success stories of wide adoption of some stove designs have also been reported in the literature. It is reported by Thurber et al. [330] that after 2006, more than 400,000 *Oorja stoves* were sold in India, and the success is largely attributed to marketing of the stove in specific regions, combined with reduced costs of its operation that attracted LPG customers to this stove. One of the most popular heavy stoves in south India, *ASTRA ole* was successfully adopted by users due to saving in fuel as well as cooking time, smoke free kitchen environment, and durability of stove for more than 10 years. [331]. A cost–benefit analysis by Mehta and Shahpar [332] showed that for users, adoption of improved cookstoves was more cost-effective than using cleaner fuels like LPG, though the latter gives much better health benefits.

A study conducted in Haryana, India showed that two of the advanced biomass cookstoves, *Philips* and *Oorja* substantially reduced PM and CO emissions as compared to traditional cookstoves. However, acceptability of *Philips stove* was higher than that of *Oorja stove* due to some limitations of the latter *viz.* difficulty in procuring fuel pellets for which it was designed, consequently operational problems with other biomass fuels [333]. The challenge of supply of prepared fuels can indeed serve as an opportunity for providing employment to the local youth. This can be done with the use of small scale pelletizing machines by local entrepreneurs for compacting locally available agricultural residue rather than a centralized supply of prepared fuel using very large scale machines. This can also help in reducing the cost of prepared fuel. Similarly training the local residents in maintaining the cookstove or even assembly/fabrication using prefabricated critical parts can be an entrepreneurial activity at the local level.

7.3. Some observations on adoption of cookstoves

The adoption of improved cookstoves are governed by several factors including the performance of the cookstove in the field, user-friendliness of the design, its maintenance requirements and special requirements of the fuel if any. Some important observations in this regard are as follows:

(a) If the fabrication of cookstoves does not involve a stringent quality control, variation in critical dimensions of the cookstove during fabrication may result in the performance of the cookstove in the field deviating from its design conditions adversely.
(b) Usage over a long period may also result in performance deterioration due to change in critical dimensions owing to wear and tear or depositions in the passages.
(c) Certain components like fans or TEGs require maintenance support by trained service personnel, lack of which can affect the long term adoption of the cookstove.
(d) If the cookstove requires prepared fuel, its availability and cost play a very important role in the acceptance of the cookstove by the user.
(e) If the operation of the improved cookstove is similar to that of the traditional cookstoves, the probability of acceptance of the former is higher.
(f) The cost of the cookstove plays a very important role in its adoption. This aspect needs to be taken care of at the design stage.

8. Concluding remarks

8.1. Conclusions

The salient conclusions that can be drawn from the available literature can be summarized as follows:

(a) A combination of forced draught and gasifier mode of operation – the latest technology in cookstoves – is highly favorable to low emissions. However, capital cost, running cost and maintenance requirements of these stoves are higher. Dependence on battery can be an environmental hazard; recharging of batteries creates a dependence on availability of electricity, while use of TEGs can be much more expensive.
(b) The gasifier stoves require small sized prepared fuel either as pellets or chopped fuelwood. Supply of the fuel in this form and its cost can be a constraint in the adoption of the cookstove and must be taken care of by the manufacturer/dissemination agency, preferably through employment generation schemes for local youth.
(c) Due to the complexity of phenomena in a cookstove, mathematical modeling and simulation cannot be used as a substitute for experiments to any great extent, particularly for predicting emissions. Modeling can help in relative evaluation of designs.
(d) There are many subtle as well as gross differences between the different cookstove testing protocols in terms of specifying the operating conditions. It has been brought out that high level of repeatability in the laboratory is very important, keeping the uncertainties in the measurement process statistically low. The measures which can substantially reduce this uncertainty include (i) avoiding the boiling of water during a test, (ii) keeping the water temperatures during high power phase as well as simmering at more than 5 °C below boiling point, (iii) using a lid, (iv) precisely defining the fuel characteristics, fuel feeding rate, pot shape and size and the quantity of water to be taken during the test.
(e) A discussion on protocols has also brought out the ongoing dilemma between the repeatability of test results in the laboratory and the extent to which such tests are representative of field conditions. It emerges that it is necessary to look at characteristics of the cookstove at different levels of fuel burning rate to adequately describe the working of a cookstove under different conditions. Thus, a single number such as efficiency or specific fuel consumption cannot adequately represent the performance of any cookstove.
(f) The rating of cookstoves in Tiers 0–4 based on their thermal and emission performance is a positive step proposed in WBT protocol 4.2.2, and this should be widely used through appropriate policy frameworks.
(g) There is lack of unanimity in the literature on relationship between fire power, efficiency and emissions. These contradictory reports have been explained in this paper through a qualitative analysis. The analysis suggests that (i) the efficiency *versus* fire power curve should look like a shallow inverted bowl and (ii) CO should show a minimum over a certain range of fire power. Both these trends are supported by a few authors. The conflicting monotonic trends in efficiency and CO with power could thus be due to restricted range of fire power levels investigated in these studies, hence capturing only a part of the overall shape of the characteristic. In certain

cases, no clear trend is observed, which is attributed largely to the scatter in the data due to measurement uncertainties.

(h) To explain the opposing trends in CO emission–efficiency curves reported in the literature, it is suggested that for a given stove, the range of power at which maximum efficiency occurs may not necessarily overlap with the range of power at which minimum CO emissions are observed. The entire spectrum may not be captured by a test over a limited power range, and depending on the power range presented by an author, the correlation between efficiency and CO emissions could be positive or negative, leading to apparently conflicting results.

(i) It is essential to back up measurements with statistical analysis to add credibility to the measurements. Most of the published literature is not backed by such analysis, resulting in difficulty in using such data to draw concrete conclusions.

(j) Many field studies report a discrepancy between laboratory and field tests suggesting that laboratory data should not be used for making global projections. In the field, the deviation from expected performance could be due to several factors. Change in critical dimensions of the cookstove in the field from their design values could be an important contributor and needs to be taken care of at the design for manufacturing stage. Use of prefabricated critical parts around which the rest of the stove could be built is an approach which has brought very good dividends in some programs.

8.2. Suggestions for future research

The current review of literature has also brought certain gaps in the field of cookstoves, which need to be addressed through future research efforts. The salient of these have been highlighted below.

(a) **Cookstove design and development**: The literature has clearly shown the high performance of the advanced biomass stoves. However, there is a need to focus on drastic reduction in the costs of these stoves through innovative designs and by exploring the possibility of using locally available materials. In this context, the research on natural draught cookstoves must be kept open, since these have the potential for effective, low cost options. Design process should take into account increasing the life of a cookstove through better choice of materials, ease of operation and maintenance.

(b) **Cookstove modeling**: Using a judicious mix of CFD and simple algebraic modeling can be useful in developing more optimal designs of cookstoves. Fundamental research on basic phenomena in cookstoves leading to the development of cookstove simulation and optimization models through painstaking and experiments and/or CFD or other detailed simulations are necessary. Mathematical modeling and simulation can also help in sensitivity analysis. This in turn can help in avoiding such values of design parameters, a small change in which can lead to a drastic deterioration in performance.

(c) **Testing of cookstoves**: There is a need to develop testing protocols for developing cookstove characteristics rather than one or two numbers for efficiency. Further research is necessary on development of a more generic methodology to produce the link between laboratory data and expected performance in the field. There is also a need for more extensive research to scientifically identify the optimal range of values of the operating parameters for testing a cookstove, like fuel characteristics, fuel feeding rate, shape and size of the pot, quantity of water *etc*.

(d) **Fuel supply, maintenance and sustenance issues**: The supply of prepared fuel for advanced biomass stove is a very important factor which needs to be addressed along with the design and development of cookstoves. The same is true of maintenance of such cookstoves. Efforts in this direction require development of reliable small scale pelletizers or improvement in those available in the market. The stove designers/promotion agencies should make efforts to liaison with the local population to train them to make or service such cookstoves. The cookstove program can then be more than a welfare program and can possibly move towards self-sustenance.

Acknowledgments

The authors would like to gratefully acknowledge the insightful comments of Prof. T.C. Kandpal of IIT Delhi and Dr. Veena Joshi of Swiss Agency for Development and Cooperation, India on the earlier versions of the manuscript.

Appendix A. Supplementary information

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.rser.2014.09.003.

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